Z E S Z Y T Y   N A U K O W E   P O L I T E C H N I K I   P O Z N A Ń S K I E J
Nr 15 Architektura, Urbanistyka, Architektura Wnętrz 2023
DOI: 10.21008/j.2658-2619.2023.15.11

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GRAPHICAL DELIMITATION OF SETTLEMENT UNITS. A TOOL FOR ASSESSING THE COMPACTNESS OF THE URBAN STRUCTURE IN THE CONTEXT OF THE TOD INDEX EXAMINATION

The article presents the original, mixed method of determining the range of individual settlement units within the existing administrative areas. Using GIS tools and raster graphics processing programs, it is possible to delimit urbanised clusters also in rural areas, for which no separate statistical and spatial data is collected. Additionally, thanks to the application of the presented method, it is possible – in some cases, to indicate the centrality of a given settlement unit, even in the absence of a spatially crystallised place, such as a square or main public park. The tool can be used on a subregional and local scale both to identify compact building structures in order to value them in terms of spatial order and to study their potential for transport-oriented development.

Keywords: urban development, spatial delimitation, delimitation methods, TOD index

1. INTRODUCTION

One of the most common phenomenon that urbanisation process entails is the tendency of mixed use as regards rural development [Stasiak 2000; Bukraba-Rylska 2008]. It is in particular visible around large agglomerations that have spread to annex urbanised villages, where one family or multi-family houses prevail, or villages with cultural and educational services, tourist functions, landscape parks, sanatoriums or similar wellness facilities, sacred places, local crafts as well as villages with

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industrial functions accompanied with prefabricated housing estates [Ziobrowski 2008; Pontius et al. 2008].

Spatial form and planning as well as location of such rural settlement units may have a significant impact on their further development. Dispersed villages may have no crystallising centre with social and business functions. According to Gzell [2013], compact building structures within urban-rural settlement units, on the condition that they maintain balance between developed areas and open spaces, in these green areas, constitute one of determinants of spatial order. Gzell defines compact building structures as spatial development shaped in the form of cohesive, whole and complete urban complexes, characterised with suitable fit-out, adequate in view of their nature. Professor Śleszyński [2013] defined relevant indicators of spatial order. One of them was dispersion/high density (compactness) of residential housing. However, he so writes when describing the indicator: “It is a basic problem to define dispersion (or its reverse phenomenon, i.e. high density) in a way that would include criteria or conditions of distance between structures. What’s also important – though only for technical issues and measurements – is the availability of data on existence of dispersed development and its relations with registered population”.

Professor Zuziak [2010], indicating features of urban forms that underlie the formation of “logical interrelations” within a transport network, listed the following:

- development intensity and compactness of building structures,
- models of area use (level of concentration and diversity of use),
- street grid geometry,
- tissue morphology,
- distribution of focal points/centres of activities (mono/policentrality),
- integration of functional and spatial structure and level of mutual interrelations (integrity/connectivity),
- cohesion, low potential for conflicts,
- land value distribution,
- spatial structure of ownership.

In localities of dispersed development, attempts to create an attractive centre of a village may entail the tendency of locating therein new development, which might successfully reduce costs of required technical and road infrastructure [Prus 2015; Cervero, Radisch 1996; Križek 2003; Naess 2005]. Spatial development intended to reduce the travelling distance by increasing accessibility of basic services creates an alternative for a car (the dominant means of transport). High density, intensive building area combined with a wide range of services blended within the residential development may effectively reduce the travelling distance and make walking or cycling more practical and cost efficient. In some cases compact development may also facilitate better management of urban cargo transport (consolidation of dispatches, planning deliveries, etc.) [Deakin 2001]. Delimitation of compact building structures by way of identification of spatial layout and concentration of certain densities in the existing structure of development as well as distribution of population may facilitate not only the delimitation of borderlines of respective settlement units but also their assessment in view of development integrated with collective (public) transport, e.g. TOD.

The purpose of the research is the development of methodology for the assessment of settlement units in view of their potential in relation to TOD (TOD index). The article presents joint, inter- and transdisciplinary approach to research with the use of two original methods of data analysis. The research problem has been solved from the perspective of an architect, an urban planner and a transport planner.

Introduction of the article presents theoretical basics of how to create compact building structures in view of the existing transport infrastructure. The article next moves to discuss selected publications connected with research on interconnecting factors of spatial development of settlement units and integrated therewith transport system. In the further part, the article presents the original method of valorisation and results of experimental calculations. The article ends with a discussion of research results and conclusions and suggestions for further analysis. This is followed by an appendix with a list of references.

2. THEORETICAL BACKGROUND

Those researchers who searched for interdependencies between proper parameters of settlement units and rationality in spatial management in view of transport planning [Pushkarev et al. 1976; Duany, Plater-Zyberk 1991; Cervero et al. 2002; Still 2002] acknowledged the role of factors related with area accessibility, mixed use development and its compact building structure. In order to define suitability of a settlement unit for the implementation of TOD, Singh [2014] and his team proposed a multifaceted analysis taking into account various densities, structures of area use and development as well as parameters of economic growth. Therein he suggested questions that any area administrative bodies need to ask:

1. What are the said various densities? To obtain the highest efficiency of public transport, increased density of housing and services is required, it is calculated as follows:
   - residential density,
   - population density,
   - density of service points,
   - density of development.
2. To what extent is the area development diverse? Higher diversity of land use reduces the number of automobile travels and thus, increases the vitality and safety of places of social interaction.

3. Is the urban design encouraging for walking and cycling? Proper area development, appropriately equipped and fitted public spaces and their high quality of aesthetics facilitate walking and cycling.
4. What is the level of economic growth? A higher number of enterprises translates into a higher level of business growth, which increases the purchasing power of the inhabitants and profitability of services.

In the studies presented herein, the authors have decided to focus on quantity analysis and to work out a method that could render answers to the first two questions.

For the purpose, they started the studies with the search how a surface area unit that should become the subject matter of further analyses could be identified.It seemed only natural that transport zones (Transportation Analysis Zones – TAZ) should be viewed as such units. TAZ zones are the spatial units that are the most frequently used in conventional models of transport planning. Their size is different and most often depends on the model range, type and density of development and location. Spatial range of a TAZ, depending on assumptions of a given model, may include very extensive areas, e.g. the suburbs or very small areas such as urban tower blocks, shopping malls, office tower complexes etc. From a technical point of view, such areas can always be allocated to single address points.However, for the reason that they are (or strictly speaking their centres of gravity) the starting points and destinations of travels, each represents a separate row and column in calculated demand matrices and index matrices. Therefore, the number of zones directly affects the design load.

Despite theoretical methods of delimiting the borderlines of transport zones, in practice they most often converge with area (territorial) units. It is often due to availability of data describing the social and economic characteristics and spatial development (i.e. explanatory variables, descriptive variables). Thus, for example for a model encompassing an administrative region [Polish: 'województwo'], transport zones are typically rural communes and in case of towns – housing estates, census areas, etc.

The explanatory variables concerned most often take into account the number of inhabitants (with their demographic structure), number of working people, ratio of vehicles to people (number of cars per 100 of working people), number of work places, number of pupils/students accepted to schools, office space, commercial and trade premises, number of offices, cinemas, theatres etc. This information facilitates better understanding of travels "initiated" from and "attracted" to respective regions [Martinez et al. 2009]. The aforementioned variables (in particular pertaining to pretty large and non-normalised areas) have made the use of TAZs for the purpose of our analysis here unsatisfactory.

Similarly to [Bertolini, Papa 2015], my interpretation of TOD is related to a wider area scope, where the entire urbanized area – and not just a single settlement unit – is transit-oriented. Therefore, the "TOD degree" is understood as the level of correlation between the connection of the railway network and the density distribution in the entire urbanized area.

3. MATERIALS AND METHODS

Data on population density on the scale of grid suitable for the planned analyses was of key importance for our considerations. Unfortunately the data of theCentral Statistical Office (GUS), apart from large urban agglomerations, is only available for a 1 square kilometre grid, which is a too much aggregated parameter. For that reason, we have decided to use data from WorldPop (2018) database created in collaboration with Bill and Mielinda Gates foundation.This data, recorded in Geotiff file format projected to WGS84, presents the population density per each pixel of the image. The data is then totalled and referenced to data collected in respective countries. Detailed information on the acquisition of demographic data recorded in Geotiff file format can be found on the website of the foundation.

Therefore, we have mainly used the following sources of data for our analyses:

– The National Database of Topographic Objects (BDOT) – BDOT10k,
– Open Street Map,
– WorldPop database for the grid 100 m × 100 m as per 2020 (Worldpop, 2018).

Next, the data in vector and raster formats has been imported to QGIS environment and processed. The processing included the following steps:

1. First, a grid of one square of 1 hectare surface area (of the side length of 100 m) was created on the set area delimited with the borderlines of Poznań metropolitan area.
2. The grid of 100 m × 100 m was mapped on the prior imported data in the raster format on the estimated population density in Poland as at 2020 and raster statistics was extracted via the application of a dedicated vector-raster overlay algorithm, i.e. for each feature of an overlapping polygon vector layer, pixel statistics of a raster layer was calculated. As a result, we have determined the population per 1 hectare.
3. Data acquired from BDOT10k in the vector format contained among others information pertaining to development such as surface area of development and number of storeys. This has allowed us to first of all allocate values related to particular objects (surface area of development and number of storeys) to units as identified from the grid of 100 m × 100 m. Next, within the units, we have calculated the values for the so allocated objects. As a result, we have obtained the map of development density for the same grid that was prior used for determining the population density.
4. The aforementioned data recorded on grids in the form of separate vector layers has been standardised and visualised in a cohesive manner. This has allowed us to overlay the grids and verify them.
5. The last set of data that was used by us in our analyses was the BDOT10k and OpenStreetMap data concerning the transport infrastructure. Like in the case of development, data was available in vector format and pertained to such compo-

nents as: road network (subdivided into categories of roads), railway network, collective (public) transport stops/stations, railway stations, etc.

A set of data on the grid population has been integrated with data sets created during the national census and used for the analysis of land use. Moreover, data on railway networks, underground train and tram lines has been acquired from the geographical databases OpenStreetMap (OSM).

Our analyses of reference literature have identified the following basic location factors that underlie favourable grounds of a given settlement unit for the implementation of TOD strategy:

– densibility described as a ratio of a centrality to surface area of a unit delimited as high density building area,
– mixed use development expressed as a ratio of service points located within the centrality to other points located in high density building areas,

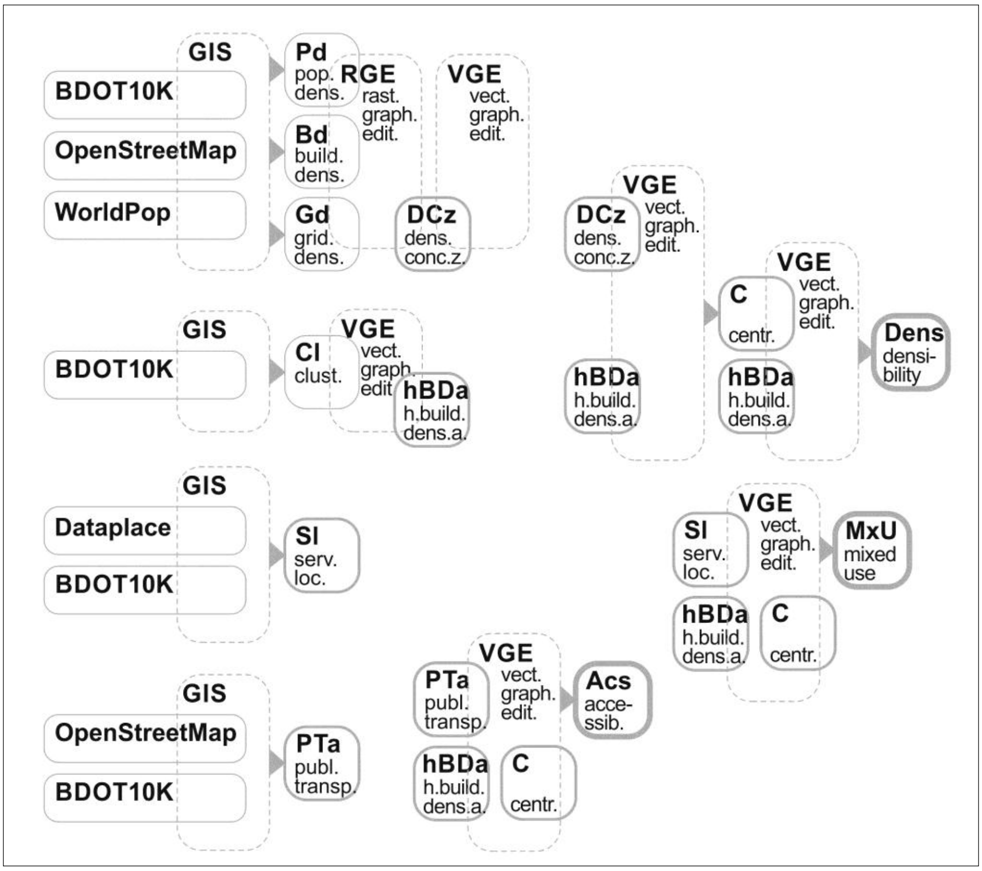

Fig. 1. Research methodology scheme [authors'own study]

– accessibility defined as a ratio of surface area of a centrality situated within the range of impact of a railway station/bus stop/station (within the radius of 1000 m from a railway station and/or 500 m from a bus stop/station) to the whole surface area of the centrality.

The mixed method, developed partly on the basis of empirical trials, consists of examining three factors, the combination of which allows for a final assessment. The individual phases of the study are shown in the illustration (Fig. 1).

4. RESULTS

In stage one, we moved to delimit density concentration zones. Based on statistical and geolocation data, we have generated on the grid maps that visualise spatial distribution of respective densities, i.e.:

– population density (number of persons per 1 hectare),
– density of development (area of development per 1 hectare),
– density of the urban grid (number of intersections per 1 square kilometer)[1].

In order to maintain cohesion between the above named layers, each has been normalised and next divided into 3 equal sub-divisions. As a result, bitmaps have been created, representing spatial distribution of respective densities by means of coloured grid squares on the basis of the monochromatic colour schemes that represent respective sub-divisions. Only the squares showing medium or high densities have been the subject matter of further analyses. Connecting all the maps by overlaying colours has allowed us to identify distribution of concentration zones of the analysed densities.

Respective densities have been marked on each map with the following colours: population density – blue (a), density of development – red (b) and density of the urban grid – purple (c). Next, the maps have been overlaid with a raster graphics processing program in a manner, where colours of respective maps could mix and form spots of the colours resulting from mixing the three original primary, monochromatic colours (d). Effects of overlaying the maps are presented in figure below (Fig. 2).

It has been assumed that density concentration zones will be characterised with the highest level (H) and with the medium level (M) of all densities under the assumption that to ensure vitality to centralities, population density was a priority prerequisite. Such an assumption is based on the observation that areas of industrial and warehouse development typically showed the highest density of development ratio.

[1] As there were few nodes in the transport network per 1 hectare, it has been resolved to use the grid of 1000 m × 1000 m.

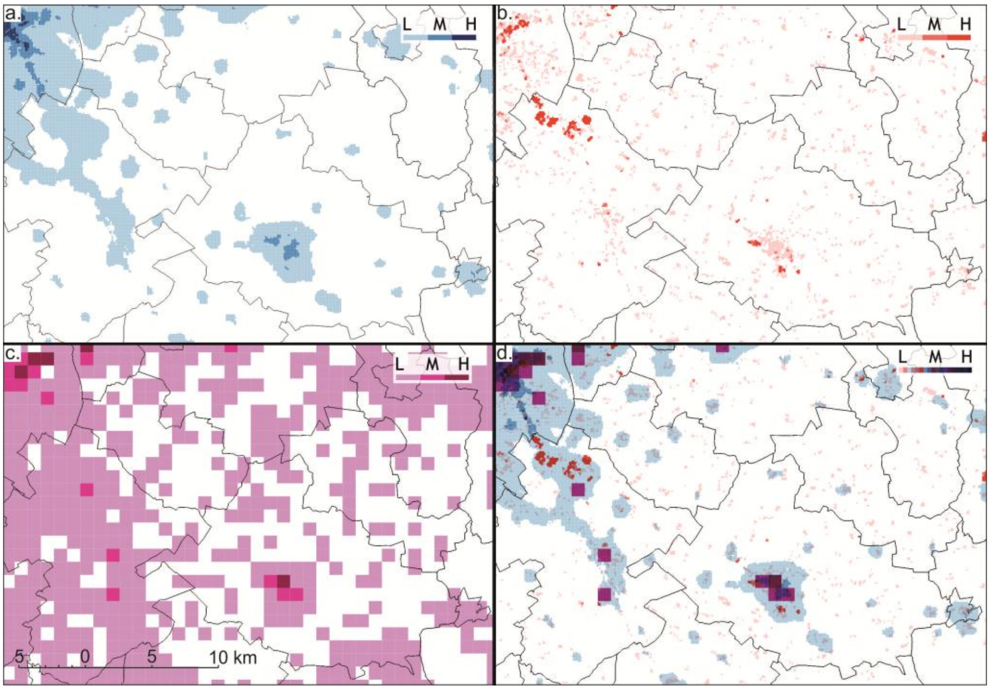

Fig. 2. Further stages of delimiting density concentration zones [authors'own study]

Therefore, population density shall be a decisive factor in delimiting centralities because this factor will entail demand for collective (public) transport, stimulate development of services and creation of work places, and justify the location of public spaces. Having juxtaposed the colour schemes that correspond to collective values, we have sampled colours falling in M and H level ranges. Next, ranges of selected areas that formed density concentration zones characterised with the highest and medium concentration levels of all densities have been converted into the vector format (Fig. 3)[2].

The article assumes that densibility is understood as a ratio of the surface area of a centrality to a high density building area delimited by means of the identification method of development concentration zones. The method is based on the algorithm which calculates and schedules buildings situated in a set distance from one another (Fig. 4).

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[2] The research as presented at this stage makes up part of the research project entitled *Modern methods of planning settlement structures in the context of sustainable development*financed from0112/SBAD/0173.Within the framework of the research, raster data for the Poznań metropolitan area has been converted into the vector format by Patrycja Pelikant, master engineer architect.

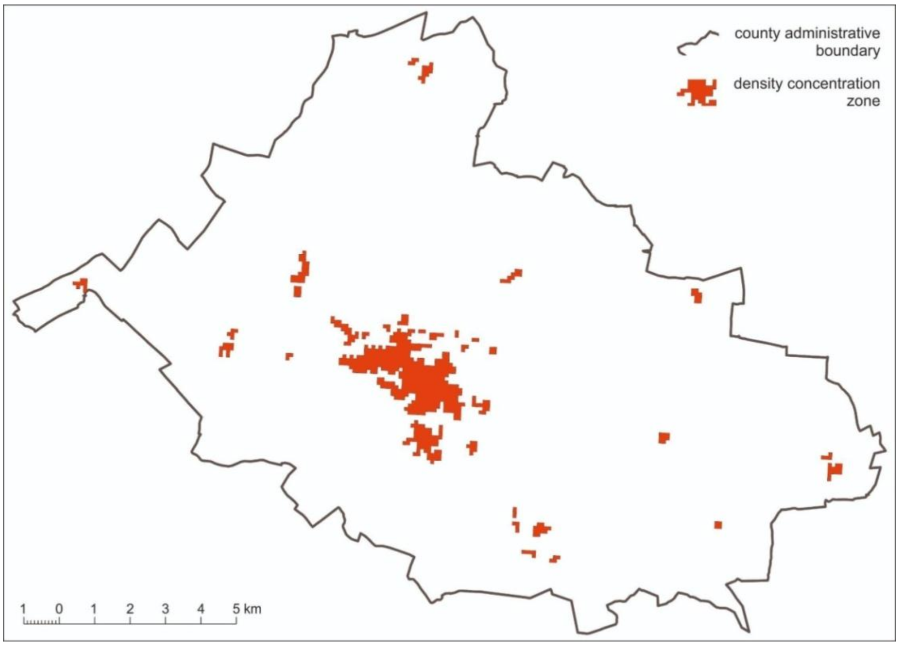

Fig. 3. DCZ – density concentration zone [authors'own study]

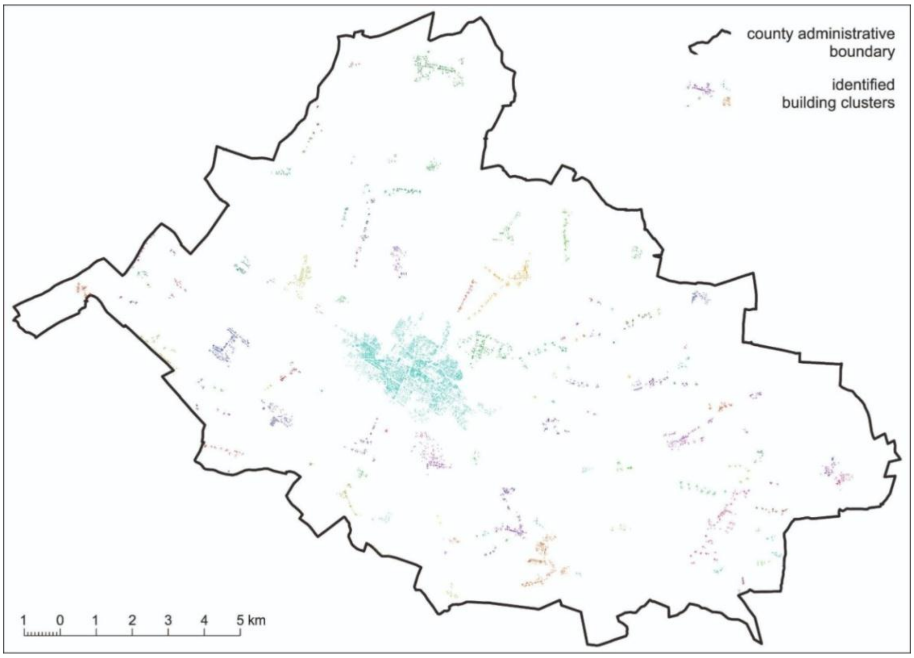

Fig. 4. Clusters – groups of points that represent centroids of respective buildings which meet the criteria set in the algorithm [authors'own study]

The applied algorithm creates clusters/groups based on the information on the concentration (high density) of observed [objects] in space. The term "concentration" ("high density") shall be understood as distances between the observed [objects] in a given area. The algorithm requires that the minimum distance to the neighbouring [object] be set.In effect not all of the observed objects have to be allocated to groups/clusters. All those objects that fail to meet the assumed criteria are deemed as outliers. In the algorithm applied, the selection of proper model parameters is of key importance. The followingareused as parameters of the model:

– epsilon (*Eps*), i.e. the neighbourhood radius, that is the minimum distance between two observed objects in order to deem the objects as neighbouring,
– min_samples (*MinPts*) – minimum number of observed objects in order to deem the selected observed object as a central point (centrality) of a given group.

Even though there are only a few parameters, selecting them in a manner that would render an appropriate number of groups – in which outliers would not represent a major part – poses the highest difficulty. The modus operandi is as follows:

– For each observed object we shall identify its neighbouring objects situated with respect to one another closer than the assumed Eps value.
– Each observed object that has at least *MinPts* number of neighbouring objects at a distance shorter than Eps is called a reference point.

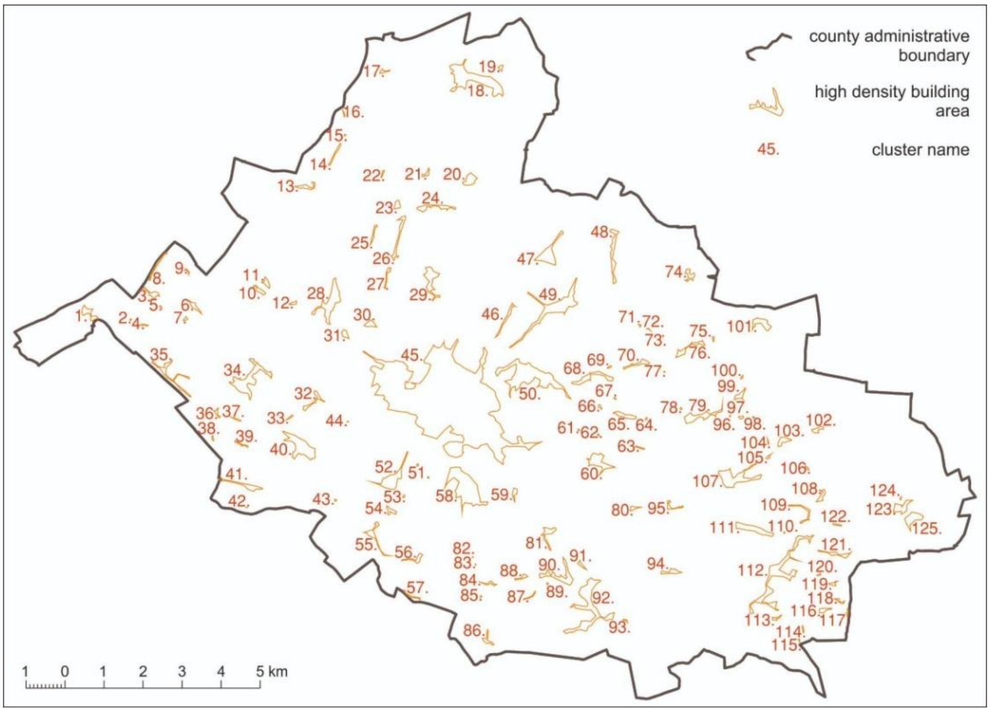

Fig. 5. HBDA – high density building area [authors'own study]

– All observed objects that meet the above criteria are classified into one group.
– Observed objects that are not reference points but are situated with respect to one another at the Eps distance get included in the existing groups.

Here, the work of the algorithm is completed and observed objects that belong to groups but have no new observed object within the Eps distance in their range are called the minimum/maximum limit objects of the group. All observed objects that have failed to be allocated to any of the groups are the outliers.

In order to make calculations in compliance with the above presented algorithm, each building has been reduced to one point (a centroid of development surface area outline). The calculations rendered groups of points – clusters that represented respective development concentrations. Next, external points of clusters have been linked, as a result we have arrived at high density building areas (Fig. 5).

These were next used to calculate densibility, i.e. ratio of the centrality (understood as a common part of high density building areas and high density (concentration) zones) to high density building areas.

$$C = HBDA \cap DCZ$$

$$Dens = \frac{C}{HBDA}$$

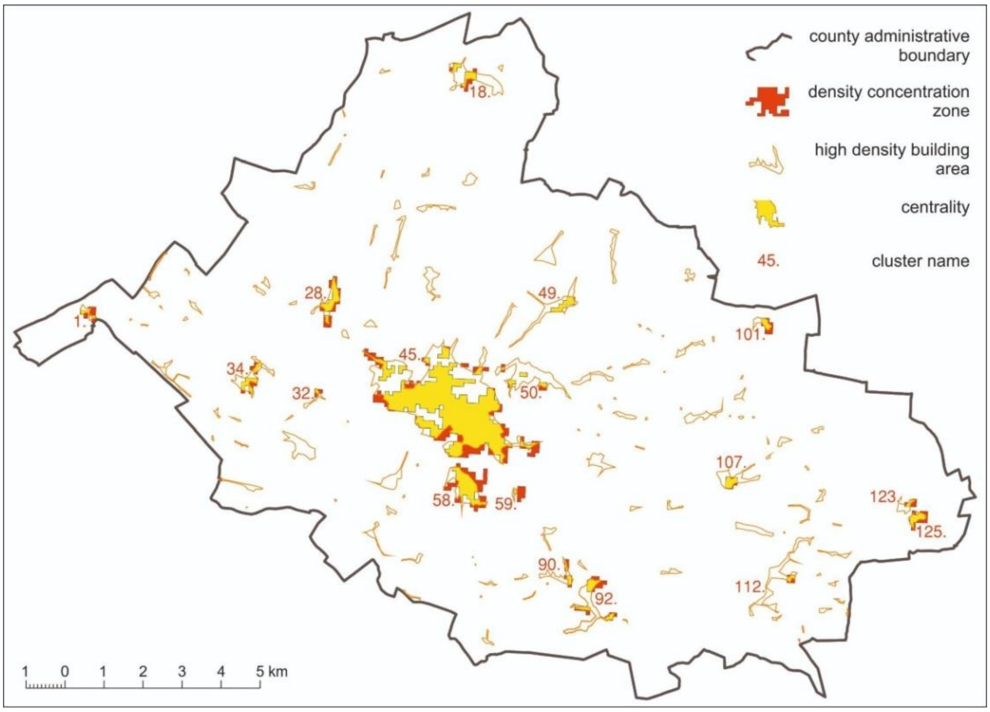

Fig. 6. Centrality[authors’own study]

According to the adopted method, densibility – required for the implementation of TOD – is a feature of units that meet the criteria of a centrality, therefore, only such settlement units were selected for further research studies (Fig. 6).

The list of selected settlement units, for which densibility has been calculated, is presented in the table below (Tab. 1).

Tab. 1. List of densibility (Dens) calculations for selected settlement units

Name of the unit (cluster)	1	18	28	32	34	45	49	50	58	59	90	92	101	107	112	123	125
HBDA	5.5	42.1	22.4	4.1	25.9	537.8	33.1	55.9	47.6	2.2	12.7	38	7.4	22.2	34.5	7.5	9.3
DCZ	9	16	28	3	16	435	10	11	63	8	7	22	9	8	4	4	13
C	3.1	10.2	16.5	1.2	10.5	362	9.7	7.3	34.1	0.8	3.8	11.6	4.3	6.7	2.2	1.6	7.8
Dens	**56.4**	**24.2**	**73.7**	**29.3**	**40.5**	**67.3**	**29.3**	**13.1**	**71.6**	**36.4**	**29.9**	**30.5**	**58.1**	**30.2**	**6.4**	**21.3**	**83.9**

Source: authors'own study.

In further part of the research we have focused on studying the mixed use development defined as a ratio of surface area of services to residential area. Unfortunately, there is no available data on actual functions that commercial usable space in buildings serves. BDOT10k database includes service points, however, services provided in residential buildings are described in the same way as places where business activity is registered, it, however, does not have to be factually carried out at the registered address. We have successfully verified and identified the number of service points based on the data acquired from the said database[3]. We have furthermore decided to simplify the studies and to use the address points to designate services on the map as well as to calculate the ratio of services located in the centrality borderlines to the number of points located in high density building areas (Fig. 7).

As a result, units characterised with the highest condensation of service points in the defined centrality could have been identified (Tab. 2).

The research was of quantitative nature, however, it shall be extended with the quality analyses. Owing to the fact that data concerning types of services was available, it was possible to allocate respective weight to services grouped as per range of their impact expressed via accessibility on foot.

[3] Owing to the established cooperation within the framework of the research project and kindness of *Dataplace.ai* company that has access to updated data including objects and service points, we could obtain the information necessary for the continuation of further stages of the research, https://dataplace.ai/.

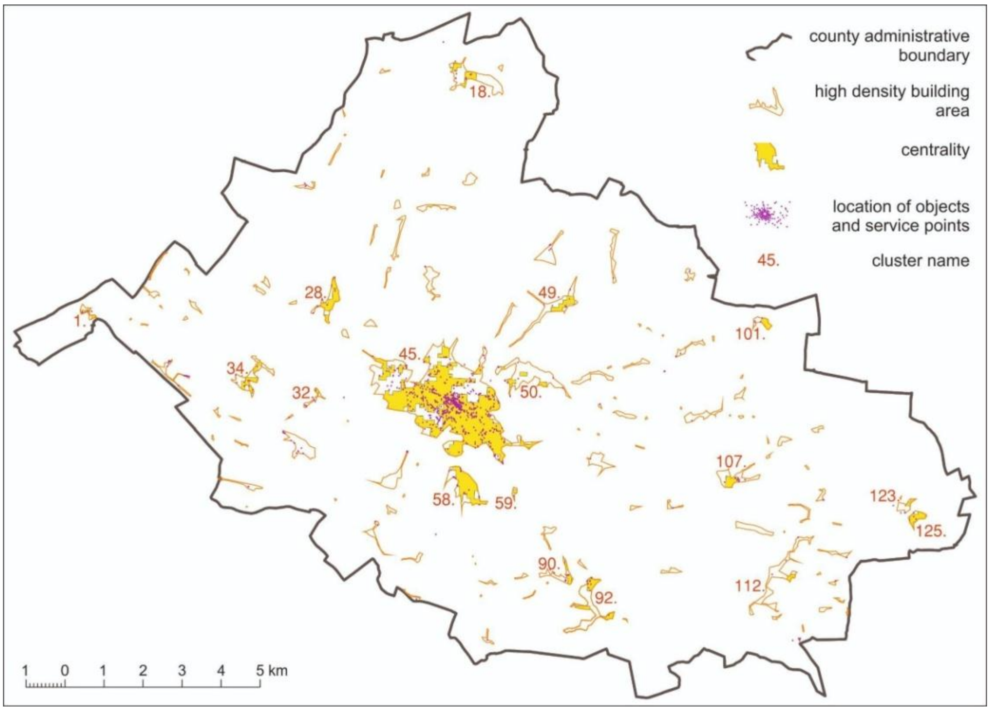

Fig. 7. Location of objects and service points (Dataplace.ai database) within the borderlines of high density building areas and the centrality [authors'own study]

Tab. 2. List of mixed use (MxU) calculations for selected settlement units

Name of the unit (cluster)	1	18	28	32	34	45	49	50	58	59	90	92	101	107	112	123	125
Number of services in the high density building area	7	9	8	5	10	620	6	9	17	1	7	9	4	9	3	1	3
Number of services in the centrality	6	6	5	1	8	520	3	0	12	0	6	8	1	3	0	0	3
MxU	85.7	66.7	62.5	20	80	83.9	50	0	70.6	0	85.7	88.8	25	33.3	0	0	100

Source: authors'own study.

Another stage was to compare the location of the centrality with respect to the ranges of impact of relevant nodes of railway and bus transport. The purpose of such studies aimed to define the degree of accessibility of the settlement units under our research. The radius of 1000 metres from a railway station and the radius of 500 metres from a bus stop delimited the accessibility zones (Fig. 8).

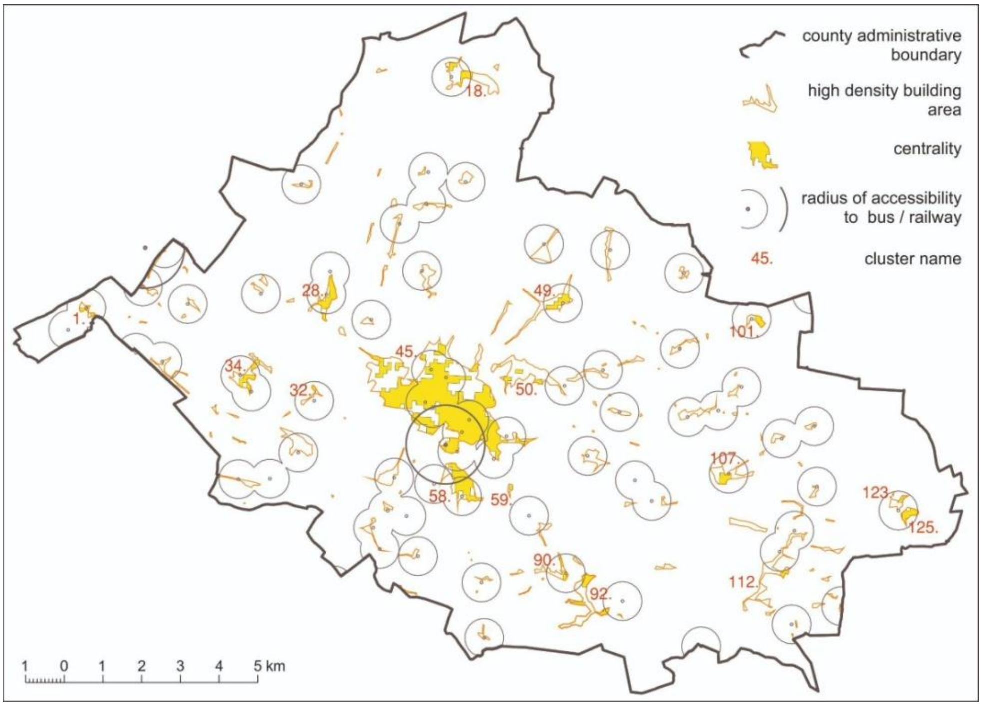

Fig. 8. Centrality of high density building areas in the range of transit accessibility [authors'own study]

This way we could make a preliminary assessment which settlement units use their location asset – namely accessibility of collective (public) transport within their ranges of impact – to the highest degree.

Tab. 3. List of accessibility (Acs) calculations for selected settlement units

Name of the unit (cluster)	1	18	28	32	34	45	49	50	58	59	90	92	101	107	112	123	125
Surface area of high density building area	5.5	42.1	22.4	4.1	25.9	537.8	33.1	55.9	47.6	2.2	12.7	38	7.4	22.2	34.5	7.5	9.3
Surface area of a centrality	3.1	10.2	16.5	1.2	10.5	362	9.7	7.3	34.1	0.8	3.8	11.6	4.3	6.7	2.2	1.6	7.8
Surface area of a centrality in TOD area	3.1	9.4	15.4	1.2	9.2	268.6	9.7	0	32.7	0	3.7	2.9	4.3	6.7	1.0	1.6	7.8
Acs	**100**	**92.2**	**93.3**	**100**	**87.6**	**74.2**	**100**	**0**	**95.9**	**0**	**97.4**	**25**	**100**	**100**	**45.5**	**100**	**100**

Source: authors'own study.

Tab. 4. Classification of settlement units featuring TOD potential

Name of the unit (clus-ter)	125	1	58	28	45	90	34	101	18	49	107	32	92	123	112	59	50
Dens	83,9	56,4	71,6	73,7	67,3	29,9	40,5	58,1	24,2	29,3	30,2	29,3	30,5	21,3	6,38	36,4	13,1
MxU	100	85,7	70,6	62,5	83,9	85,7	80	25	66,7	50	33,3	20	88,9	0	0	0	0
Acs	100	100	95,9	93,3	74,2	97,4	87,6	100	92,2	100	100	100	25	100	45,4	0	0
TOD poten-tial	**94,6**	**80,6**	**79,3**	**76,5**	**75,1**	**71**	**69,3**	**61**	**61**	**59,7**	**54,5**	**49,7**	**48,1**	**40,4**	**17,3**	**12,1**	**4,3**

Source: authors'own study.

5. DISCUSSION AND CONCLUSION

Owing to the applied methodology it was possible to delimit both the borderlines of high density building areas and also of their centralities, if any. This it is particularly useful when it is not possible to identifycentrality due to no central public space that crystallises the entire spatial composition. Such a role may be played by a square or intersection of major streets with a formal or functional dominant. This is in particular typical of rural units where delimiting a 'centrality' may pose a problem.

In order to carry out proper spatial analyses, it was necessary to acquire relevant data and to respectively process it. Such data includes information about spatial development (functions, number of buildings and their sizes, designation of the area), demographic data as well as data on transport infrastructure.

This article uses the term 'settlement unit' on purpose so that no e.g. rural or urban areas be grouped into categories at the very introductory stage of the research. The previously applied divisions delimit the ranges of urban structures only administratively (as drawn on maps) and are not dictated with any true ranges of development impact. Survey precincts and areas of administrative units often divide cohesive and continuous urban structures. As a result the analysis of the acquired data does not reflect true distribution of the analysed parameters (density of development, population density, etc.). To avert the need to use statistical data that is collected based on divisions that disregard continuity of structures, we have come up with an original method of delimiting the settlement units that takes into account spatial distribution of different densities on the basis of vector maps of the existing development. The proposed method can be used without any need to acquire statistical population data, as the procedure of information acquisition on the estimated impact ranges of urbanised areas can be much simplified. Administrative borderlines marked on the maps no longer delimit but only facilitate better orientation in reading graphical data.

Determining the boundaries of urbanized areas can also be used – as in the case of the presented research – to assess the development potential in the context of planning transport infrastructure (Tab. 4). Additionally, identification of the spatial impact range of a village can help to more efficiently manage spatial development of rural areas. Owing to the application of the parameter of an average distance between objects in the local zoning plan to define the range of impact of development of a given nature (dispersed-compact), we can control and plan spatial development with the observance of spatial order.

This article has focused on the normalised approach of the research based on databases and maps. The presented method allows us to fully assess the dispersion and density of development and to a limited degree the density of services. In this respect, the generated data shall be compared with the field studies to verify results obtained via the normative method. The method is not useful for valorization of public space. In this respect, descriptive studies based on experts' analyses on physiognomy of space and opinion polls shall be deemed as more appropriate.

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NARZĘDZIE DO OCENY ZWARTOŚCI STRUKTURY MIEJSKIEJ W KONTEKŚCIE BADANIA INDEKSU TRANSIT ORIENTED DEVELOPMENT

Streszczenie

W artykule przedstawiono autorską mieszaną metodę wyznaczania zasięgu poszczególnych jednostek osadniczych w obrębie istniejących obszarów administracyjnych. Wykorzystując narzędzia GIS i programy z zakresu grafiki wektorowej i rastrowej, możliwe jest wyodrębnienie skupisk obszarów zurbanizowanych także na obszarach wiejskich, dla których nie są gromadzone odrębne dane statystyczne i przestrzenne. Dodatkowo dzięki zastosowaniu prezentowanej metody możliwe jest wskazanie zwartych zespołów zabudowy w celu identyfikacji ich jakości w zakresie ładu przestrzennego, jak i do określenia ich potencjału dla rozwoju zorientowanego na transport. Narzędzie może być stosowane w skali subregionalnej i lokalnej.

Słowa kluczowe: rozwój przestrzenny, delimitacja przestrzeni, metody delimitacji, Transit Oriented Development indeks