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Application of multi-criteria analysis in GIS for optimal planning of house development areas. Case study of Wrocław Functional Area

Zastosowanie analiz wielokryterialnych w GIS do optymalizacji planowania obszarów zabudowy mieszkaniowej na przykładzie Wrocławskiego Obszaru Funkcjonalnego

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Introduction

Design of new house development areas is a complex spatial planning problem that requires consideration of multiple conditions and factors. These include: legal, political, economic, social, technical and physiographical aspects. In the current legal frames regulating spatial planning in Poland three levels of planning activities can be identified, the first related to defining directions of spatial development of an entire administrative unit (a voivodeship at a regional scale and a commune at a local scale). Such directions are established in a voivodeship spatial development plan (*plan zagospodarowania przestrzennego województwa*) (the regional level) and study of conditions and directions of spatial development in a commune (*studium uwarunkowań i kierunków zagospodarowania przestrzennego, suikzp*) (the local level). These are not acts of law in a legal sense but provide, especially in the case of *suikzp*, guidelines for shaping the designations of local spatial development plans (*miejscowy plan zagospodarowania przestrzennego, mpzp*). The designations in *mpzp* define the rules of spatial development at a local scale, i.e. concerning development of land use zones and guidelines of building forms. Thus, each of these acts describe rules of spatial development at a different level of detail. Particular spatial conditions and factors, such as presence of areas of environmental protection or extent of an agglomeration area influences the way, in which spatial policy is conducted (Sowa and Tomczyk, 2012). In the presented study the initial, highest level of spatial planning has been considered. Taking into consideration the above mentioned legal constraints, it provides reference frames for the lower, local levels. The purpose of the study has been to identify areas suitable for new housing developments from the perspective of an "enlightened" spatial planner. That is to provide an unbiased, quantitative, GIS-based method of identification of such areas that supports decision-making and constrains processes of uncontrolled spreading of urbanized areas ("urban sprawl"), demand for valuable natural land, demand for areas threatened by natural processes (floods, landslides, etc.) and transformation of forest and rural areas into residential areas (Sowa and Tomczyk, 2012), all associated with land (housing) development.

Housing development location issues in the Polish literature have been presented for example by Bartkowski (1986), Szponar (2003), Solon (2009) and abroad by Bruegmann (2005), Lisowski et al. (2014). In a study, Díaz-Pacheco and García-Palomares (2014) have assessed the urban land use patterns, trends, and evolution on the example of Madrid in the context of the urban sprawl linked to the residential developments. Their study has shown parallelisms with other urban development models in Europe. Recent studies of housing development phenomenon around Polish cities include the work by Mantey (2013), who – on the example of the Piaseczno commune – discusses importance of various criteria for making individual decisions on place of residence and evaluation of living conditions. Jaroszewicz et al. (2012) have applied a modified Land-Use Conflict Identification Strategy (LUCIS) concept to analyse potential spatial conflicts facilitated with GIS on an example of a village near Warsaw. The growth, characteristics and underlying factors for development of suburban areas in the vicinity of Wroclaw have been described by Kajdanek (2011). Poniży (2008) performed spatial-temporal analysis of transformations in the land-use pattern beyond the limits of the Poznań city with respect to mismanagement of space and possible uncontrolled sprawl of cities and chaotic growth of suburban areas. These studies point to the same spatial, environmental, social and economic costs and problems of uncontrolled urbanization, e.g. costs associated with overestimating the size of areas for housing development, high costs of technical infrastructure development, higher transport costs, the lack of public spaces, social and spatial polarization, human relationships, defragmentation of natural areas, landscape devastation, environmental loss of resistance to degradation, etc. (Kowalewski et al., 2014).

In our study, five sets of criteria, four of them decomposed into sub-criteria have been identified, weighted and combined to produce the final solution. With this aim a staged multicriteria analysis methodology in GIS including *Analytical Hierarchy Process* (AHP) and two stage *Weighted Linear Combination* (WLC) methods have been proposed and applied for the case study of the Wroclaw Functional Area (*Wroclawski Obszar Funkcjonalny*).

The proposed methods belong to a group of GIS-based spatial multi-criteria analysis methods (also called multi-criteria evaluation methods) that allow analysis of complex, multidimensional trade-offs between choice alternatives, for example locations or suitability analysis of an area (Meng et al., 2011). The basic principle of these methods is to analyse a finite number of choice possibilities with respect to multiple criteria and different objectives (Voogd, 1983). A comprehensive review of these methods has been presented for example by (Malczewski, 2004; 2006; Drobne and Lisec, 2009). Noteworthy applications in spatial planning include the study by Bathrellos et al. (2012) who applied the AHP and the GIS-based method for an integrated evaluation of areas suitable for urban growth with respect to natural hazards and geological and geomorphological parameters, as well as research by (Donevska et al., 2012) on the landfill site-selection methodology based on the fuzzy set theory to standardize criteria with fuzzy membership functions.

In Poland, GIS-based multi-criteria analyses have been used in studies focused on the decision support of spatial planning processes at a local (commune) scale by (Hejmanowska and Hnat, 2009). The authors focused on comparison of the raster-based *Weighted Linear Combination* and the vector-based *Boolean* operator analyses for the purpose of new housing development location. They suggested that the WLC technique is more adequate for the assessment of urbanization trends, while the Boolean method is better for development of a spatial planning study. The GIS-based *Weighted Linear Combination* and *Cost-Distance* analysis methods have also been used for planning locations of linear infrastructure investments such as railway and road corridors. In a study by (Drzewiecki et al., 2012) attention has been given to the sources and quality of digital data necessary for the study and the analysis has been performed for 13 identified decision factors. Blachowski (2015) used a combination of the Analytical Hierarchy Process (AHP) and the Weighted Linear Combination to determine weights of environmental and spatial (land use) factors conditioning development of an open-cast mine project in the *Dolnoslaskie* Province and to produce an accessibility map in a geographic information system.

Materials and methods

The following two analytical methods have been combined in GIS in the study, the *Analytical Hierarchy Process* (AHP) and the *Weighted Linear Combination* (WLC). In the AHP method proposed by Saaty (1980), the problem is analysed in a hierarchical structure, usually composed of several levels. Its basic steps include (Vaidya and Kumar, 2006): (1) definition of the problem, (2) identification of criteria that influence decision, (3) structure the problem in a hierarchy of levels constituting objective, criteria, and the optional sub-criteria and variants, (4) pairwise comparison of each element on the corresponding level in a comparison matrix, (5) calculation of the Eigenvalue, the Consistency Index (CI), the Consistency Ratio (CR), and normalized values for each criterion. Detailed description of the AHP method can be found for example in (Saaty, 2008).

The WLC method is based on the concept of a weighted average, where criteria are combined by applying a weight (in this study determined using the AHP procedure) to each of them followed by a summation of the results to yield a suitability map (5) (Drobne and Lisec, 2009):

$$S = \Sigma w_i x_i \tag{5}$$

where S is the suitability, w_i is the weight of factor i, and x_i is the criterion score of factor i.

In cases, where Boolean constraints apply, i.e. in order to exclude certain parts, the procedure is to be modified by multiplying the suitability calculated from the factors by the product of the constraints (6):

$$S = \Sigma w_i x_i \Pi c_j \tag{6}$$

where c_j is the criterion score of the constraint j.

The complete methodology developed and used for the purpose of identifying the most preferable areas for new housing development in the pilot study has been shown in Figure 1.

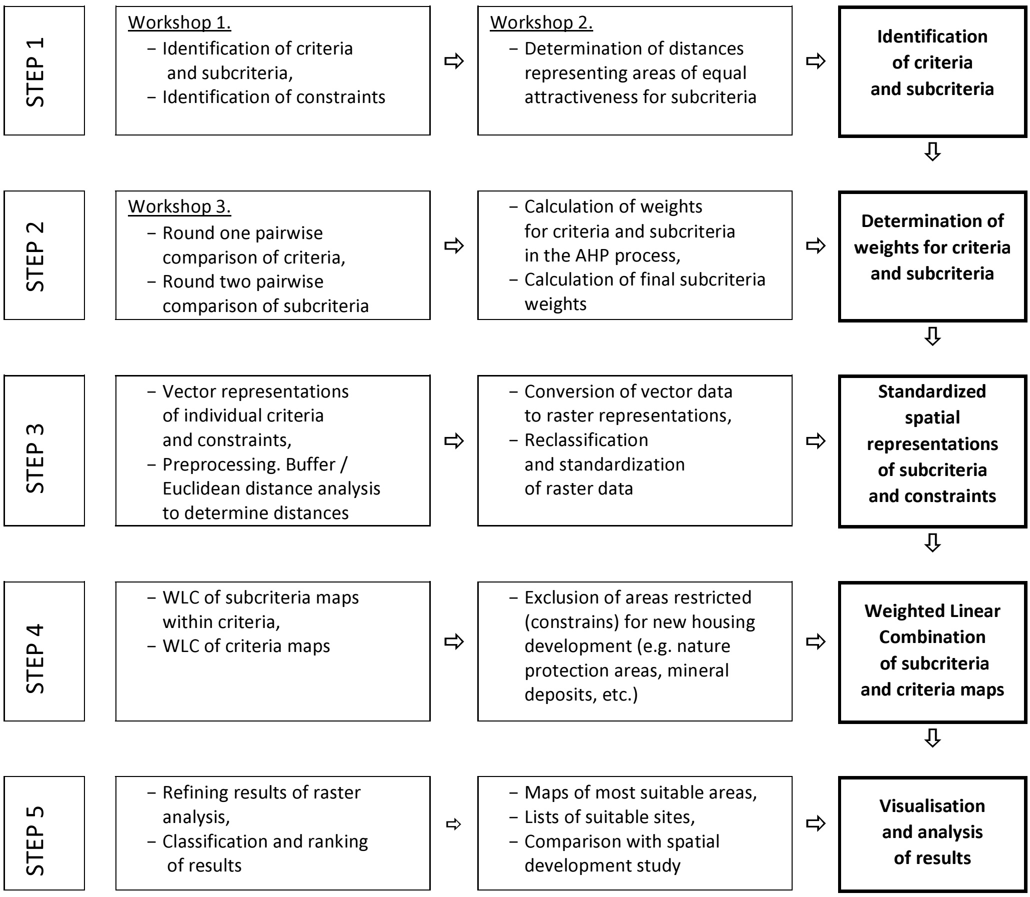

Figure 1. Methodology of identifying areas suitable for new housing development with AHP and WLC in GIS

The procedure includes the following steps (Fig. 1):

1. Identifying criteria and subcriteria conditioning suitable locations for new housing developments.
2. Developing the AHP framework model and deriving weights of criteria and subcriteria through their pairwise comparison based on judgements of spatial planning experts.
3. Developing the GIS database and single criterion raster maps representing subcriteria.
4. Performing the two stage (criteria, subcriteria) weighted linear combination analysis, and
5. Classifying and interpreting the results of suitability analysis.

Steps one and two consisted of workshops involving a group of over a dozen invited experts, academicians and practitioners, representing various specialisations associated with spatial planning that included, among others: urban and spatial planners, geographers, nature protection specialists, transport specialists. In a course of surveys this group of spatial planning experts identified 5 main criteria determining the suitability of land for new housing developments. Subsequently, for each of these groups subcriteria have been identified (Table) by the experts. For each subcriterion, 4 boundary distances representing the terrain attractiveness in terms of the distance to a particular site/object representing a given subcriterion were determined. Four boundary distances create five zones, the closest one being the most attractive and the furthest away one the least. For example for several subcriteria in the public services group the boundary distances were determined as follows: 250, 500, 750 and 1000 m, for some of them the following values were agreed: 300, 600, 1000 and 2000 m; for some other subcriteria different values were determined within the 2000 m for the boundary between the 4th and the 5th zone. In the next phase the same group of planners conducted individual pairwise comparison of criteria and pairwise comparison of subcriteria within each criterion group. Averaged judgements of experts were then specified in the final pairwise comparison matrices and used to calculate weights of criteria and subcriteria in accordance with the AHP theory. The highest calculated consistency index value was 7.3% within the limits of consistency suggested in literature. The consistency index value for the final matrix was 1.7%. The final score for each subcriterion has been obtained by multiplying the criterion weight and each subciterion weight in a given criterion group, e.g. the final weight for the distance to the tram station factor in our approach is 4.3%.

Spatial representations of subcriteria have been prepared in GIS using the source data described in the *Data and software* section. Vector data representing locations of particular subcriteria, e.g. train stations, primary schools, health centres or bank facilities have been used to calculate access distances in five concentric zones (examples of distance to churches and temples are presented in Figure 5). Then the maps of subcriteria have been then converted to raster data and reclassified to the 1 to 5 range to obtain a common numeric range for all factors. The reclassified value of 5 represented the closest and the most suitable area and the value of 1 – the furthest away and the least suitable area for location of new housings with respect to a given subcriterion. In the same way – the vector to raster conversion – spatial representations of constraints have been prepared. The identified constraints restricting location of new housing development included: nature protection areas, areas prone to flooding, water protection zones, documented mineral deposits, good quality soils and areas prone to landslides. Combined layers representing areas unsuitable for housing development are presented in Figure 6 at the end of this paper. In the study the raster resolution of the 10 m pixel size has been used for criteria representation.

The study area

The pilot study concerned the Wroclaw Functional Area in the *Dolnoslaskie* Province (SW Poland). The boundaries of WrOF identified in the following documents, *Study of delimiatation possibilities of functional areas based on NSMC 2030* (2013) *and Study of functional cohesion in the Wroclaw Functional Area* (2015) prepared in the Institute for Territorial Development, and based on the *National Spatial Development Concept 2030* (*Koncepcja Przestrzennego Zagospodarowania Kraju 2030*) have been used in the research. The WrOF area adopted in the study comprises of 44 communes (*gminy*) in 7 districts (powiats): oleśnicki, oławski, strzeliński, średzki, trzebnicki, wołowski, wrocławski, concentrated around the city of *Wroclaw*. Area of *Wrocław* has been excluded from the analysis. The study area and its location in the *Dolnoslaskie* Province is presented in Figure 2.

Table. Criteria, subcriteria and their weights obtained in the AHP process

Criterion	Weight of criterion [%]	Subcriterion (distance from …)	Weight of subcriterion [%]
Transport infrastructure	31	Train station	28.9
		Tram station	14.0
		Urban bus station	12.7
		Suburban bus station	11.7
		Trunk / Regional road	9.3
		Park & Ride site	23.4
Public services	23	Nursery	6.4
		Kindergarden	15.8
		Primary school	22.9
		Middle school	11.7
		Secondary school	2.9
		Temple	5.3
		Health centre	16.5
		Culture centre, library or community centre	5.6
		Sport centre	5.5
		Leisure facilities and recreational areas	7.3
Commercial services	4	Bank	19.8
		Supermarket / grocery	50.3
		Pharmacy	19.2
		Post office	10.7
Technical infrastructure	28	Sewage network	32.7
		Water network	32.4
		Gas network (reducing station)	16.0
		Heating network	11.6
		Telecommunication network	7,3
Housing development	15	Existing housing	100.0

Data and software

GIS tasks in the study have been realized using Esri ArcGIS v. 10.3 licensed to Wrocław University of Science and Technology. Calculations of criteria and subcriteria weights based on the above-mentioned experts' judgements have been facilitated with the AHP template developed by Klaus Goepel and available from http://bpmsg.com/. Maps representing subcriteria have been prepared based on databases of national public administration organisations in accordance with their statutory tasks, in particular the data extracted from the Topographic Objects Database described in (Dz.U. 2011 no 279 pos. 1642, Dz.U. 2015 pos. 2028), databases obtained from other units of the Dolnośląskie Marshal Office and from other public administration bodies such as the National Water Management Authority and the Polish Geological Institute, databases managed by the Institute for Territorial Development and data prepared solely for the purpose of this study. The latter included locations of bank agencies, post offices, pharmacies, supermarkets and groceries and have been developed through a survey of information posted on commune and county websites, databases of organizations and institutions. The spatial accuracy of criteria representations has been set to the 10m pixel size of maps representing distances from the considered subcriteria and the adopted boundary distances determined in the process of expert discussions.

Results and discussion

Results of the significance analysis of criteria and subcriteria, carried out in the group of experts mentioned above and utilising the two-stage AHP methodology, revealed that the groups of transport infrastructure (31%) and technical infrastructure criteria (28%) are the most important for balanced and optimised location of new housing development. These groups were closely followed by the access to public services (23%) and distances to existing housing areas (15%). The access to commercial services was not considered to be important, reaching 4% of the total score. The factor which has not been onsidered in the analysis, and, according to our opinion, which should be taken into consideration in further studies, is the ecophysiographical background of the area. In the transport criteria group, the access to public transport networks and park and ride sites was determined to be the most important. In the public services criteria group, the access to schools and preschool facilities, as well as health centres turned out to be the most important whereas, in the technical infrastructure criteria group, the most important factors are sewage and water networks. Unfortunately, due to the limited availability of spatial data this criterion has been omitted from further GIS analysis. Based on the analysis of the pilot study result and the locations of the chosen sites we assume that this did not affect the reliability of the final results. However, this criterion will be included in the future analyses concerning the local level.

The linear combination of standardised representations of subcriteria (distance from locations) has been performed in the following stages: (1) the first maps for particular criteria have been created, (2) they have been combined into a single land suitability map in the two-stage GIS procedure described above, and finally (3) restricted areas have been removed from this result using the raster calculator function. Areas unsuitable for housing development (restrictions) are presented in Fig. 6. Aggregated maps for 4 criteria (transport infrastructure, public services, commercial services, distance to existing housing development) are shown in Figure 7 to Figure 10 respectively, and the final suitability map for housing development can be seen in Figure 3.

As the result of this pilot study 47 areas in the most suitable class have been identified (marked in dark green in Figure 3). The results have been refined to exclude sites unsuitable for development such as small areas or problematic shapes. After these procedures the final set has been reduced to 28 suitable sites. Bearing in mind that the access to technical infrastructure has not been considered at this stage of research, the areas considered to be the most suitable for housing development obtained scores 3.2 to 4.0. The selections in the most suitable class range in area from 500 sq meters to 113 500 sq meters with two even larger sites in Trzebnica and Oleśnica. The largest ones are located in the neighbourhood of existing built-up areas in or next to villages and towns in the study area. The total area in the most preferred class exceeds 98 ha. A representative site for the selected set of locations are shown in Figure 4 together with remaining lower suitability classes the existing housing development (from BDOT 2015) and compared with content of the most up to date ortho-image. In the process of refining the results, several separate pixels have been removed. The site covers the area of approx. 6300 sq m and is relatively small comparing to the available area. This has been caused by the strict boundary values of distances accepted for the analysis and classification of results. However, different scenarios with different values can be tested in practice. The soft characteristics of the output of the WLC analysis does not allow for a direct and precise designation of boundaries but it is a recommendation for planners and planning procedures including comparison with the existing plans.

Conclusions

The study presents the AHP and the GIS-based methodology to facilitate solving of spatial planning problems concerning the optimum location of a given type of land functions such as the sustainable and balanced selection of new housing areas to minimize economic, environmental, social and other types of costs of such decisions for local communities and inhabitants (Kowalewski et al., 2014). It can be also applied to support the decision-making processes concerning different types of spatial planning issues, such as the location of sites of economic use or individual investments, providing impartial quantitative and qualitative information on the assessed area. The pilot study results for a relatively large area of over a dozen communes (*Wrocławski Obszar Funkcjonalny*) indicate the efficiency of the applied GIS multicriteria analysis methodology in identifying suitable housing sites and supporting the sustainable development of housing areas around a metropolitan centre. The raster based approach facilitates the use of significance weights of individual factors in calculations and application of the AHP models and provides means to qualitatively assess their relative weights. The individual operations can be automated in GIS, further streamlining the entire procedure. The assumed distance values separating the attractiveness classes for the analysed crtieria and the number of classes (5 in the study) can be modified to fine tune the analysis and also to test and compare different spatial planning scenarios.

The limitations of raster-based WLC procedures, such as the related generalization of spatial representation of criteria and the soft, continuous character of the products hindering location of precise boundaries necessary in urban planning processes, are cause that in most cases the results cannot be directly used for making the decisions. However, bearing in mind that the present planning documents do not correspond with a staged development of housing areas and that the extent of planned spatial development clearly exceeds local needs and that it is not correlated with conditions existing in a given area, they provide means to quantify and visualize the available spatial conditions clearly pointing to the areas of interest that in many cases might have been omitted in the planning process providing a decision support tool for spatial planners and decision makers.

The study has also revealed that up to date, the high quality and complete databases describing the conditions in the analysed area are essential to conduct the research process correctly. Databases and web map services provided through implementation of the national spatial information infrastructure allow to relatively easily acquire most of the necessary data and compare the results of analyses with provisions of spatial development plans and aerial images presenting the current land use in GIS.

The results of our study provide information on the character of housing development around the city of Wrocław and identify areas that should be utilized for housing development in the first place thus limiting adverse effects of uncontrolled development that does not take into account costs of such decisions. The problem brought up in this pilot study is now further investigated in more details at a local scale and with a different set of parameters as a Master of Science thesis at the Wrocław University of Technology and with the assistance of the Institute for Territorial Development.

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Abstract

The paper presents the methodology of planning house development areas and discusses results of works related to identification of the optimum areas for such development, performed using the example of the Wrocław Functional Area (WrOF) in Dolnoslaskie Province.

For the needs of the analyses of the land suitability for housing development, performed from the perspective of the rational planner, the multicriteria analysis in geographic information systems (GIS) was proposed. The applied methodology includes identification and determination of criteria and subcriteria weight which determine the optimum location of housing areas and the double weighted total of maps representing the analysed criteria in space. The basic, considered criteria included: the transportation infrastructure, the technical infrastructure, public services, commercial services and the existing housing areas. A set of subcriteria which determine location of development sites were defined in each group. The basic criteria, subcriteria and their significance were determined as a result of the questionnaire among the group of experts (in spatial planning, public administration, science, nature) with the use of the Analytical Hierarchy Process (AHP) The two-stag, weighted, summing of subcriteria and criteria was performed, areas which limited or which did not allow for locating housing areas were eliminated and then the analysis of results and the preliminary evaluation of the spatial coherence of determined and real locations of areas planned for housing development was *performed using the local planning documentation. The proposed approach – by means of standardisation and quantification of factors which influence the locations of investments – allows to minimise the subjective intentions of a planner and it supports planners through presentation and visualisation of real spatial conditions of investments.*

Streszczenie

W artykule przedstawiono metodykę wyznaczania terenów predysponowanych do lokalizacji zabudowy mieszkaniowej oraz omówiono wyniki prac związanych z identyfikacją optymalnych terenów pod taką zabudowę, przeprowadzonych na przykładzie Wrocławskiego Obszaru Funkcjonalnego (WrOF) w województwie dolnośląskim.

W badaniach przydatności terenów pod zabudowę mieszkaniową, z punktu widzenia racjonalnego planisty, zaproponowano metodę analizy wielokryterialnej w systemach informacji geograficznej (GIS). Zastosowana metodyka obejmuje identyfikację oraz określenie wag kryteriów i podkryteriów determinujących optymalną lokalizację terenów mieszkaniowych oraz dwukrotną ważoną sumę map reprezentujących analizowane kryteria w przestrzeni. Wśród kryteriów podstawowych rozpatrywano: infrastrukturę komunikacyjną, infrastrukturę techniczną, usługi publiczne, usługi komercyjne oraz tereny istniejącej zabudowy mieszkaniowej. W każdej z grup zdefiniowano zbiór podkryteriów determinujących lokalizację zabudowy. Kryteria podstawowe, podkryteria oraz ich istotność określono w wyniku ankiety grupy ekspertów (planistów przestrzennych, administracji publicznej, przedstawicieli nauki, przyrodników) z zastosowaniem metody hierarchicznej analizy problemu decyzyjnego (Analytical Hierarchy Process – AHP). Dokonano dwuetapowego ważonego sumowania map podkryteriów oraz kryteriów, wyeliminowano tereny ograniczające lub uniemożliwiające lokalizację terenów mieszkaniowych, a następnie przeprowadzono analizę wyników i wstępną ocenę zbieżności przestrzennej wyznaczonych oraz rzeczywistych lokalizacji terenów przeznaczanych pod zabudowę mieszkaniową na podstawie lokalnych dokumentów planistycznych. Zaproponowane podejście, przez standaryzację oraz kwantyfikację czynników warunkujących lokalizację inwestycji, pozwala na zminimalizowanie subiektywnych odczuć planisty oraz stanowi wsparcie dla planistów przez przedstawienie i wizualizowanie rzeczywistych warunków przestrzennych lokalizacji.

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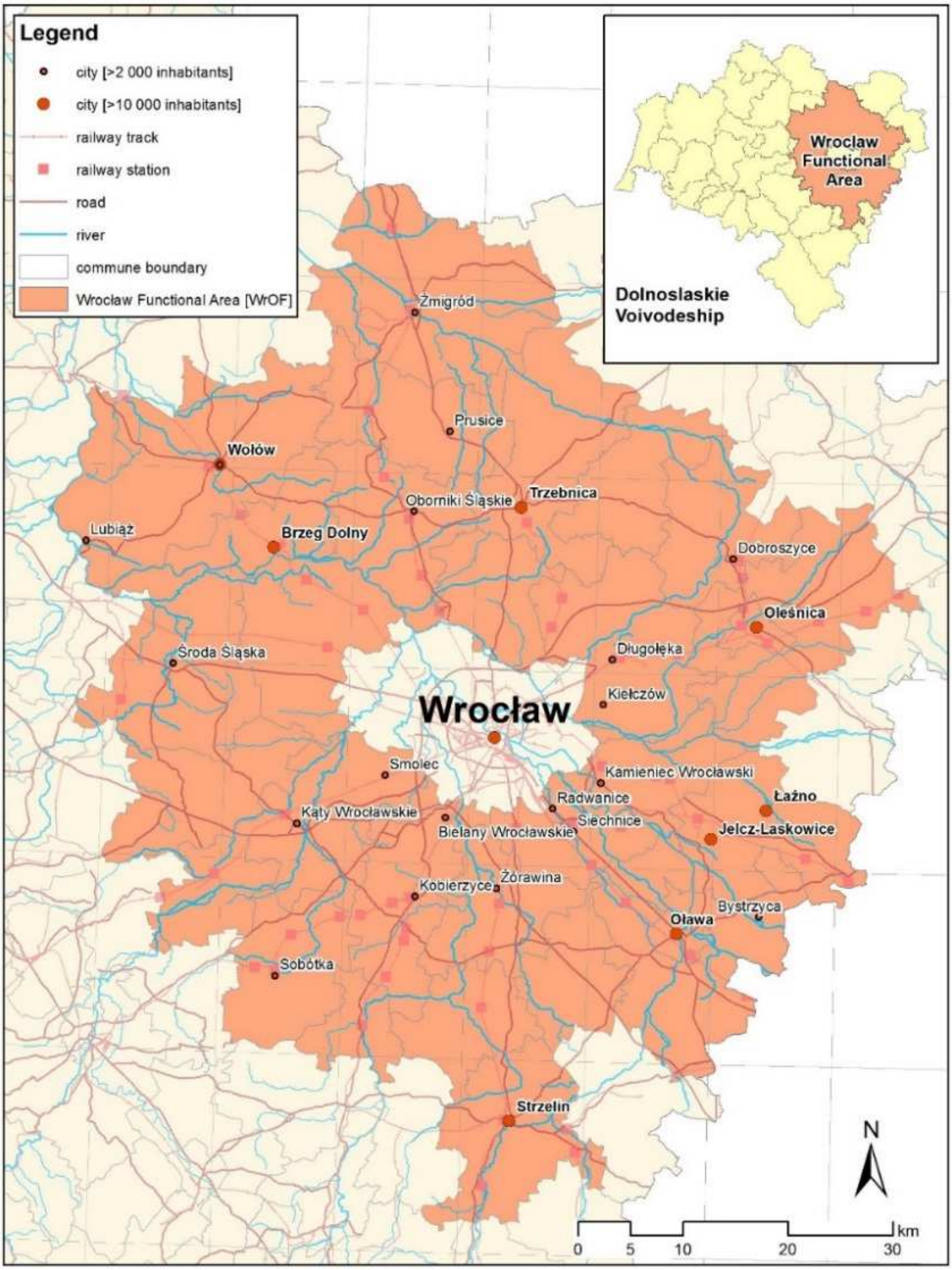


Figure 2. Location of the Wroclaw Functional Area in the Dolnoslaskie Province

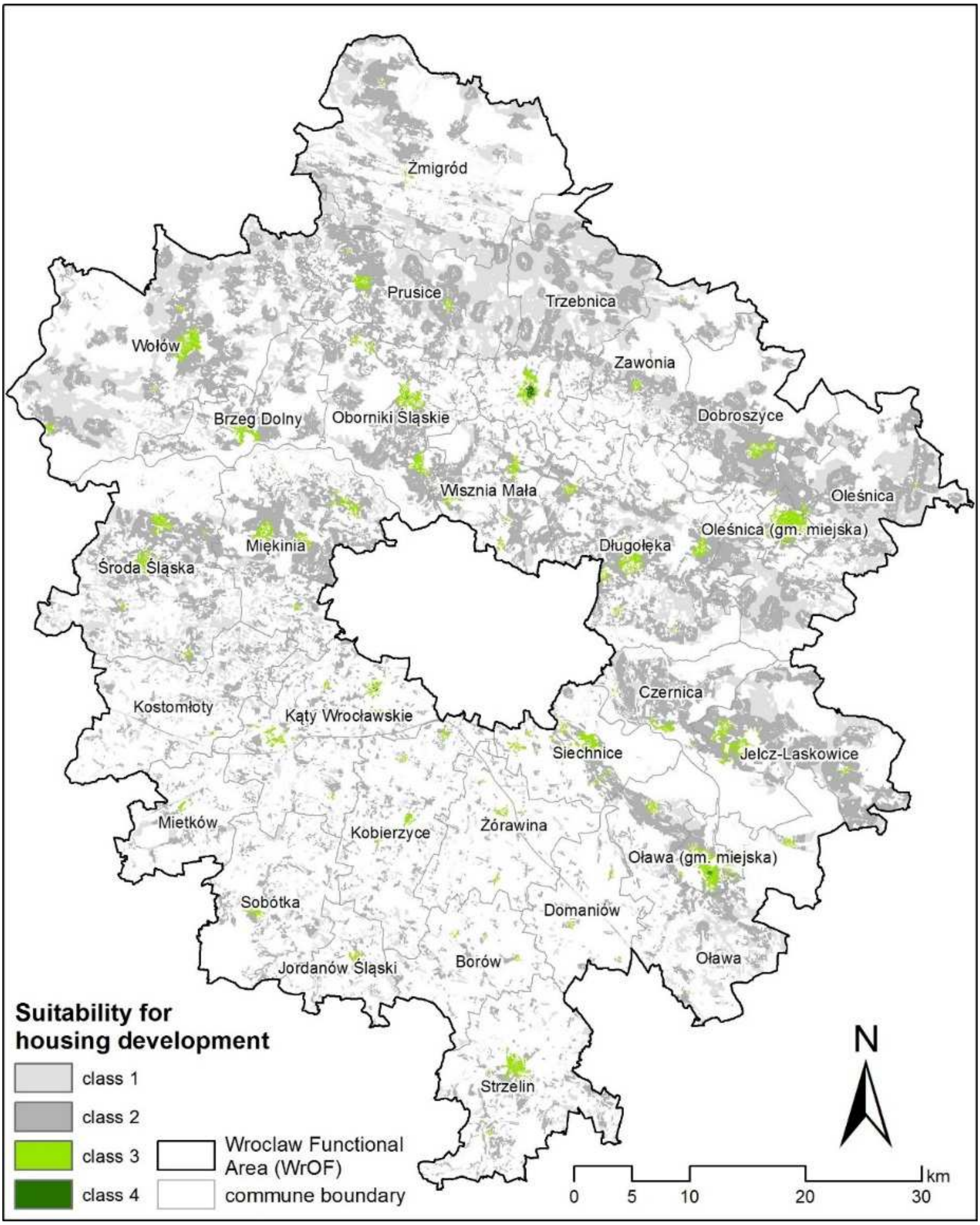


Figure 3. Final map representing the land suitability for new housing development

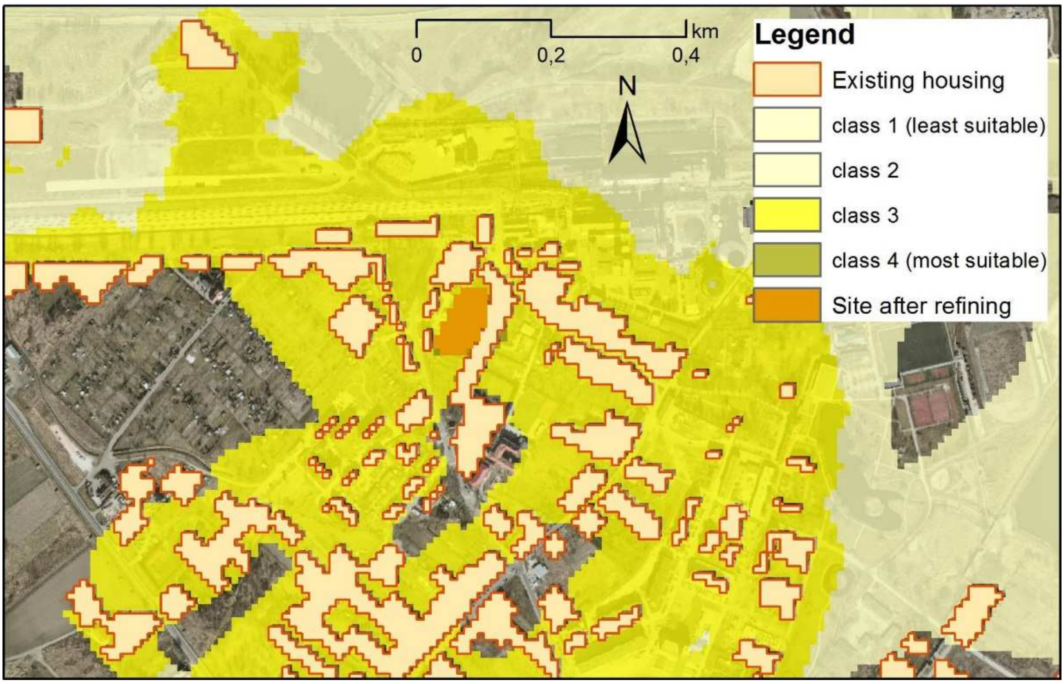


Figure 4. The land suitability for new housing development in one of villags
in the Wrocławski District (powiat)

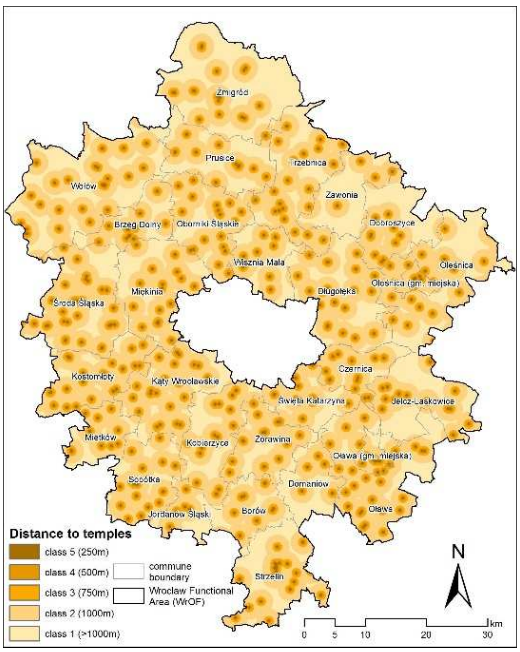


Figure 5. Example of the subcriterion map
(distances to temples and the boundary distances
accepted in the study)

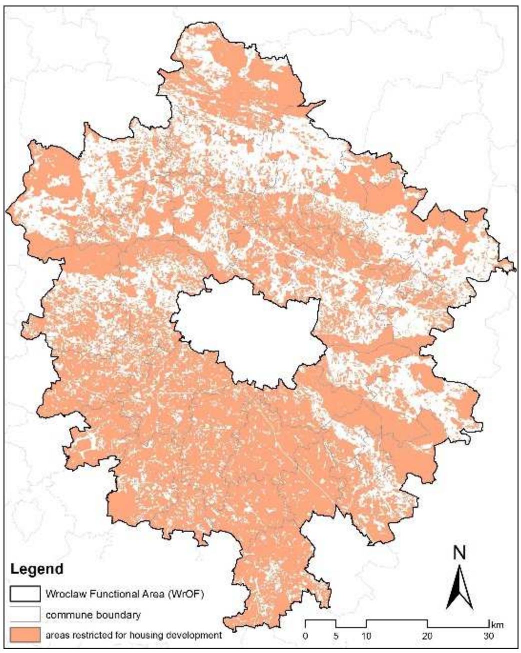
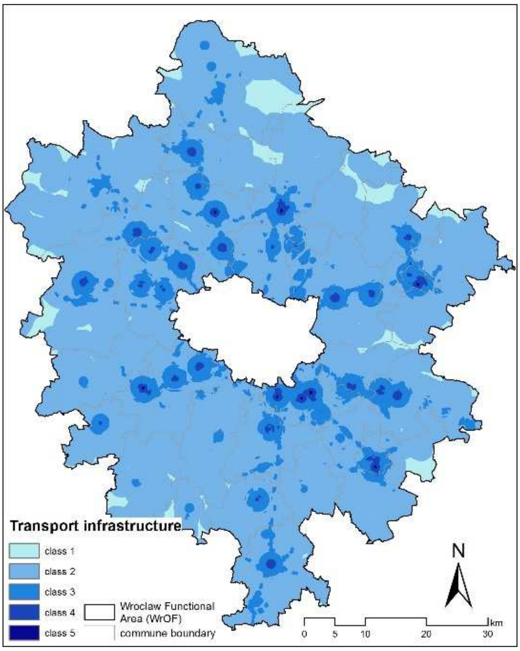


Figure 6. Areas unsuitable for new housing
development



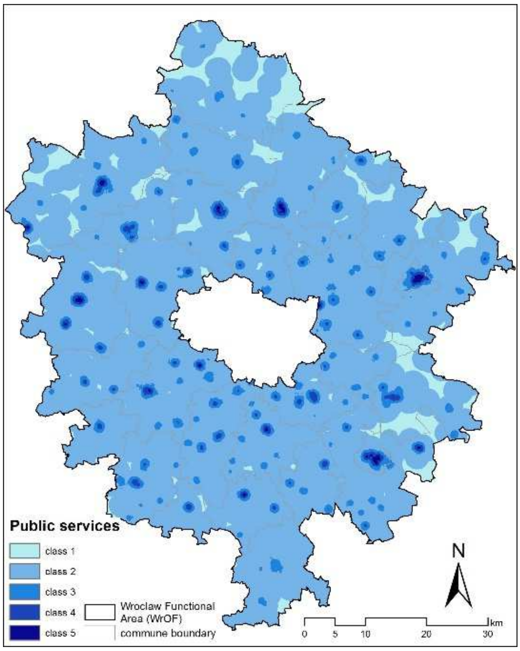
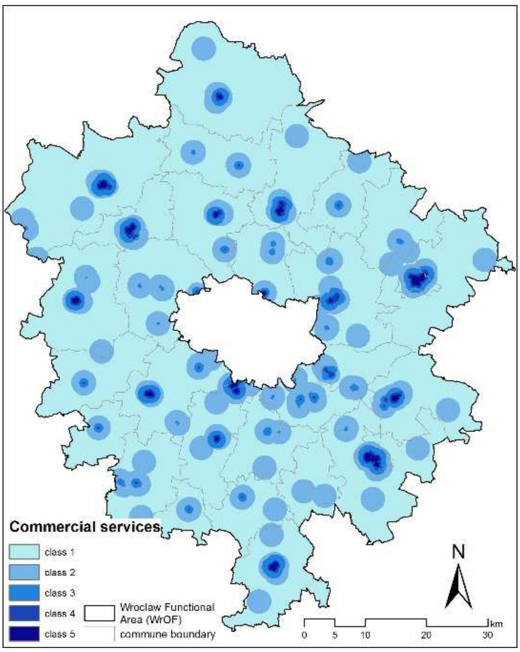


Figure 7. Results of the WLC analysis for transport infrastructure criterion

Figure 8. Results of the WLC analysis for public services criterion



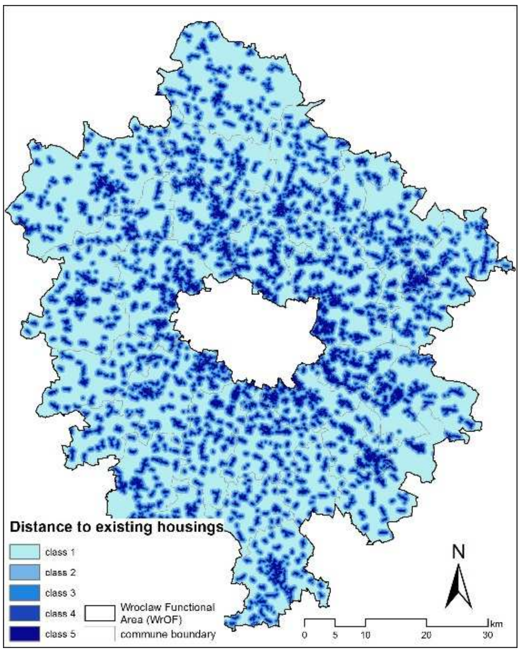


Figure 9. Results of the WLC analysis for commercial services criterion

Figure 10. Results of analysis for distances to existing housings criterion