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DOCTORAL THESIS

-Summary-

Implementation of geographic information systems (GIS) in the analysis and forecasting of territorial development. Case study: Cluj-Napoca Metropolitan Area

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CONTENT

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INTRODUCTION

The majority of the population in advanced countries, and an increasing number of people in developing countries, live in large and densely populated metropolitan areas (Krugman, 1998). Rapid global urbanization is a significant challenge for today's society and the future. In 2008, the number of people living in urban areas exceeded those living in rural areas for the first time (UN, 2008). According to United Nations projections (UN, 2022), by 2050, 68% of the global population will live in urban areas (up from 56% in 2021 and 25% in 1950).

The phenomenon of urbanization, and implicitly, that of territorial development, involves a considerable degree of uncertainty. This is because, often, spatial growth and expansion are carried out conjecturally in the absence of carefully worked-out strategies and plans, especially in the early stages of development. The growth and expansion depend on numerous variables, such as environmental conditions (morphology, climate, hydrography, and resources in general), advantage of position, social-economic and/or political conjuncture, individual and group interests, conflicts of interest, and more. In this way, the elements of constraint and urban dysfunction gradually exacerbate, and over time, the costs of overcoming the errors produced in the absence of articulated scenarios or plans for responsible territorial development become increasingly high.

The present study deals with fundamental aspects of *territorial development* consisting in the *analysis and prediction of probable and desirable changes that may occur in the spatiotemporal condition of this exceptionally complex and urgently topical phenomenon*. The approach is based on the premise that territorial development is an *interface phenomenon* situated between the manifestations of a number of defining, causally interconnected contemporary processes, with the most important being *population growth, economic progress and urbanization.* Additionally, it considers the legitimate need of human communities to manage, as sustainably as possible, the wide-ranging structural, functional, and spatiotemporal transformations brought about by these processes.

The present approach is *motivated* precisely by the aspect highlighted above, namely the *exceptional importance of diagnosis and forecasting in the context of judicious and responsible planning of territorial development*, including the desire to make a useful personal contribution in this regard. However, beyond this general, well-known and unanimously accepted statement, our intention is to *build and establish (as far as possible) a new methodological system* which, taking advantage of the opportunities offered by geographic information systems and satellite imagery, allows us to interrogate and interpret, in a logical sequence, the correlations and multiple effects of the interactions between the many variables operating in the spatial dynamics of urbanized territorial systems. In order to be able to capture conclusive mutations of this kind, the first step in carrying out the research was to *choose an appropriate study area*, in this case the Cluj-Napoca Metropolitan Area, a highly representative administrative region at national and continental level due to the accelerated process of urban expansion.

Accordingly, the *general objective* of this paper is to *investigate, determine and apply the most appropriate methods and practices for implementing GIS and remote sensing technology in the process of analyzing and forecasting spatial development, as seen from the perspective of built-up areas expansion and changes in land cover and land use patterns*.

The working hypothesis from which we start *derives from the legitimate assumption that there might be a certain approach that* (in the sense of the concept of scientific method) *is likely to be followed much more expediently and conclusively by GIS users in their attempts to quantify and decipher the defining spatial configurations of territorial dynamics*. In other words, the aim of our research is to search for, achieve and test a possible *model of investigation based on a proper, well-argued and, implicitly, veridical algorithm that would provide an accurate diagnosis (analysis) of the state of the territory able to allow,* in turn, *the deciphering of optimal scenarios of subsequent design and planning*.

In order to achieve the general objective, a series of *intrinsic requirements (specific subsidiary objectives)* of the research have been constantly taken into account, leading to the adequate definition of the problems, a viable flow of information and a complex working methodology, developed in accordance with recent technological progress, which makes use of spatial and statistical data and remote sensing images, extremely useful tools in the process of territorial analysis, planning and development.

We consider that the most important *specific subordinate* (subsidiary) *objectives*, able to confer originality to the work and, implicitly, to prove the existence of a valuable and significant personal contribution, were the following: the elaboration of a conceptual reference framework in line with the most recently accepted concepts in the literature devoted to the analysis and prediction of territorial development; the investigation, determination and implementation of the best methods and techniques for processing, extracting and integrating spatial data relevant to the subject studied, both on the basis of remotely sensed images (satellite and aerial images) and spatial and statistical data from various sources; the creation of geospatial databases and determination of how they can be better integrated into the targeted analyses; the multi-temporal analysis and assessment of territorial changes in the context of built-up areas (urban growth); the development of forecasting scenarios based on machine learning algorithms and dynamic models for simulating territorial transitions; the analysis of the suitability of the territory for different types of development; the creation of cartographic materials based on the results obtained.

Following the stages mentioned above, we consider that, as a whole, our research, proposed as a doctoral thesis, has eventually been divided into two distinct and, at the same time, essential parts of any study of this nature.

The first part, focused on the ***theoretical foundation*****,** aims at researching and recording the most important theoretical aspects in the literature, both in relation to territorial development and the complexity of urban systems, and to spatial indicators for assessing development dynamics at the level of relevant geographical units (metropolitan areas and/or functional urban areas, urbanization and urban growth, i.e. assessment of development potential and forecasting), as well as on geographic information systems, remote sensing, geospatial data types, methods and practices used for analysis, modelling, representation, assessment and forecasting of territorial development.

The second part of the study is the ***practical (applied) part***, focusing on the creation and integration of spatial databases, the processing of satellite and aerial images and the extraction of geographical features and relevant information in the context of territorial development. It also includes spatial analysis and digital modelling, multi-temporal assessment of territorial change, forecasting and analysis of the suitability of the territory for different types of development.

CHAPTER 1 - CONCEPTUAL ASPECTS AND CURRENT STATE OF KNOWLEDGE

The first chapter of the thesis aims to define and describe the theoretical basis and legislative foundations of territorial development, as well as the application and utilization of geographic information systems and the multitude of methods, techniques, and data with which they operate in this process.

To achieve optimal, integrated, and rational urban spatial planning based on scientifically-based complex spatial analyses, it is essential to understand the structural elements and defining characteristics of the urban system, the urbanization process, the dynamics of urban growth, and other urban-related processes, so that the modelling of complex spatial systems can closely reflect reality.

Territorial development is a multi-faceted concept that plays a crucial role in shaping the economic, social, and environmental landscape of a geographical region. Over time, the concept has been the subject of research in various fields, including geography, economics, urbanism, spatial planning, and others.

The initial studies on development as a process came from the field of economics, which led to some, but not universal, agreement in the scientific world that the term "development" refers to a process that results in economic growth. However, this approach is limited, as it is based solely on economic criteria. It is essential to recognize that development can be approached from different perspectives, and its study is a broad, interdisciplinary field.

A quick review of the literature shows that the notion of development has no clear theoretical basis. As a result, a fully acceptable and universally applicable theory of development is neither possible nor desirable. Regardless of the field used, however, we can conclude that "development" implies change, evolution, and often growth or progress resulting from a comparison with a previous stage.

In geography, development refers to space, specifically territory, whether local (urban or rural), regional or global. It includes both its physical, environmental, and socio-economic components. The concerns of geography in relation to development relate to improving the standard of living and quality of life for human communities. They are often focused on the study of spatial patterns in relation to development so that the spatial characteristics of development and how this process is influenced by social, economic, cultural, political, and environmental factors can be determined and measured. However, viewed from a broader multi-temporal perspective, development can have both positive and negative implications.

Urban development is a key aspect of territorial development that focuses on the city as a center of economic growth, technological and scientific innovation, and coordination for the surrounding region. Given the complexity of urban development, it is important to thoroughly analyze the mechanisms and their interrelationships that form the foundation of the urban system.

The concept of the „urban system" derives from regional geography, traditional macro-level urban analysis, and regional economics. The terminology was originally used by Duncan et al. (1960) in their efforts to impose functional organization on metropolitan areas in the United States. Subsequently, Berry (1964) introduced general systems theory to urban geography through the study of empirical rules in urban, regional, and national areas (Simmons, 1981). Urban geography emphasizes the importance of city or urban area size and functional variation. Particularly important is the fact that urban systems are multi-layered and can be identified both as individual urban settlements (cities) and as networks of such settlements.

Cities or urban networks formed in the territory have always been an important factor in the development and shaping of nearby regions, significantly influencing the landscape through polarization phenomena in the urban-rural space (Retsilidou and Atzopoulos, 2013). This paper considers that the epicenter of a well-defined urban system is the city, which, due to its complex structure, must be analyzed both from the point of view of its internal structure and especially from the point of view of how it interacts with the neighboring territories, forming real functional urban areas.

Urban development is a form of territorial development, and the broader concept of urban development implies change in the sense of growth and decline. In contrast to decline, growth implies the shift of non-urban activities and spaces into the urban environment. The physical aspects of urban growth are directly related to extensions of built-up areas and changes in land cover and functional land use (Cheng, 2003).

Urban growth has two contradictory aspects. On the one hand, mega-cities act as engines of economic and social growth; on the other, most growth is accompanied by poverty and environmental degradation. Through the accumulation of negative effects, the impact of urbanization and land use change on environmental sustainability becomes globally significant (Vitousek, 1997; Cheng, 2003). Thus, faced with severe negative impacts, spatial planners need to rethink spatial development policies and manage urban growth in a more sustainable and science-based manner in the future.

Today's cities are increasingly expanding into their surrounding areas, continuously consuming the resources of the natural environment without due consideration of the social, economic, and environmental consequences. The result of this expansion is often a highly urbanized landscape with an associated technical infrastructure and uncontrolled growth patterns.

Urbanization and sub-urbanization are the distinctive outcomes of contemporary urban growth (Rashed and Jürgens, 2010). This process presents many challenges for sustainable development. Dorothy F. et al. (2019) point out that urbanization has a twofold effect on natural space: the expansion of built-up areas, i.e., urban growth, implies an increased demand for resources/energy and generates increased amounts of emissions/waste, putting increasing pressure on natural space. Additionally, urban growth leads to fragmentation, isolation, and reduction of natural and semi-natural spaces.

Thus, there is growing interest in identifying and understanding the effects of urban growth on land area and land cover change. This knowledge is essential not only for determining spatial patterns but also for establishing effective urban planning and management strategies (Wu and Zhang, 2012; Li, 2014).

Uncontrolled urban sprawl, characterized by a spontaneous evolutionary pattern, has become a major issue that contemporary spatial planning and management policies are increasingly addressing. Throughout the 20th century, limiting the sharp and uncontrolled expansion of cities towards the periphery was a priority for development and planning agencies. However, this was largely ineffective, and it is now widely recognized that urban growth cannot be controlled. Instead, there is a greater emphasis on information and analysis, which has been facilitated by the significant advancements in computer technologies (Rashed and Jürgens, 2010).

The concept of „urban sprawl" has caused confusion regarding its characteristics and impact, whether negative or positive, due to an amalgam of definitions that are not always consensual in the literature. Urban sprawl is often defined by its negative effects and impacts, which are regarded as hypotheses rather than empirically proven facts (Rashed and Jürgens, 2010).

According to the literature, the main determinants or vectors of sprawl are generally the following: an increase in income, living standards, and social demand for low-density settlements; the need to expand space for housing, industry, and/or business; the expansion of territorial infrastructure coupled with a decrease in travel times and transport costs from the periphery to the urban core; differences in the property market (cost of land) and tax rates between the urban core and the periphery; competition between administrative units (e.g. municipalities) to attract households or companies; and, in some cases, regional or national policies favoring relocation to the countryside. There are also considerable differences in the application of regulatory rules between urban and rural areas.

It is important to note that this study focuses on the manifestations of urban sprawl in the European context, although the concept may have different characteristics depending on the continent. Additionally, the literature often fails to distinguish clearly between the effects of urban sprawl and other related phenomena such as urbanization, sub-urbanization, and urban growth. In this paper, the concept is defined as a phenomenon that generally involves „*an uncontrolled expansion of built-up urban areas*" and „*dispersed urban development*" with many negative connotations resulting from uncoordinated territorial development.

As outlined above, the complexity of urban development is due to interactions between multiple factors associated with *demand, technological capacity, social relations, and the environment* (Lambin et al., 2001; Verburg et al., 2004a)

The literature on the determinants of urban growth and land use and land cover change identifies four major classes of spatial development indicators: natural, socio-economic, spatial policy, and neighborhood (Munthali, 2022). Other authors group indicators into socio-economic, political, biophysical, and technological categories (Briassoulis, 2003), which refer to similar elements. However, the accuracy of identifying these vectors is crucial for the analysis and forecasting of land use change (Munthali, 2022). Turner and Meyer (1994) and Geist and Lambin (2002) have developed a framework for analyzing vectors of influence, categorizing them into *direct* and *indirect* vectors of influence.

In this study, the socio-economic processes that are perhaps the main driving forces of physical and functional urban growth are addressed tangentially. Instead, the focus is on analyzing, assessing, and representing the spatial manifestation of urban growth, i.e., urbanization.

The spatial dynamics of urban development are embodied in two categories of processes: *the physical expansion of urban space* (first process) and *its functional change over time* (second process). The first process refers to changes in spatial parameters during the transition from rural to urban through the expansion of built-up areas and infrastructure, while the second process refers to major changes in the functional structure, such as transitions from residential to commercial areas or vice versa.

One of the most important indicators of urban development is „*land occupation*" which refers to the amount of natural land that has been converted into artificial or built-up areas, as well as „*land use intensity*" which represents the actual amount of artificial land per inhabitant (European Commission, 2014). Another key indicator used in monitoring the urbanization process is the *urbanization rate*, which is the rate of change in the proportion of the urban population.

As highlighted in the introduction, the study of urban sprawl is crucial for urban development planning and regional development strategies, and thus requires accurate and up-to-date data on built-up areas. The accurate delineation of built-up areas and the measurement of urban sprawl are significant challenges for spatial development and planning specialists. Therefore, it is essential to have timely and precise mapping of urban land to facilitate good spatial planning and rational land management. Additionally, identifying sprawl patterns and analyzing spatiotemporal changes would be of great help in the context of proper spatial infrastructure planning (Dolean et al., 2020).

The land use and land cover (LULC) in urban areas are highly dynamic from a multi-temporal perspective, mainly due to the construction of new buildings, roads, and other land infrastructure at the expense of natural land. Consequently, LULC changes serve as a robust indicator of multi-temporal spatial development, involving a more detailed level of analysis of urbanization than merely assessing built-up area expansion, i.e., the spatial-temporal analysis of the dynamics of the dichotomous relationship between built (artificial) space and natural space.

Mapping and analyzing LULC changes within urban regions are crucial for assessing the „*ecological footprint*" of spatial development and urban growth to inform scientific decision-making on land-use planning and regulatory policy options, including conservation interventions (Furberg, 2019).

Previous research (such as Barnsley and Barr 2000; Cihlar 2000; Franklin and Wulder 2002; Zhou et al. 2008; Yang 2011; Qin et al. 2013; Ban et al. 2014, Furberg 2022) has demonstrated the immense usefulness of integrating remotely sensed data into GIS spatial analyses to achieve the aforementioned goals, specifically the multi-temporal analysis and forecasting of spatial development dynamics by assessing and mapping the expansion of built-up areas and changes in land use/land cover in urban areas.

As previously noted, the territorial development processes of urban systems go beyond the administrative boundaries of territorial units. Therefore, spatial development analysis, forecasting, policies, plans, and actions related to spatial planning and development must be conducted at a level that captures the entire urban system, including all component sub-systems, in terms of spatial extent. Furthermore, it is essential to consider how the urban system integrates into higher territorial systems, such as regional or national systems.

Rashed and Jürgens (2010) suggest that the process of urbanization should be described, monitored, and simulated at different scales, depending on the issue under consideration. Analyzing and mapping the progression and gradual expansion of urbanization at a regional (metropolitan) scale provides a 'big picture' that enhances understanding of the phenomenon (Banai and DePriest, 2014).

Therefore, approaching territorial development concepts at a regional scale by selecting geographically defined areas such as metropolitan areas, functional urban areas, or peri-urban areas is more relevant.

Geographic Information Systems (GIS) and remote sensing are powerful tools that have revolutionized the way spatial development is analyzed, assessed, and forecasted. They enable the visualization and analysis, from a multi-temporal and spatial perspective, of the relationships between different geographical phenomena and processes, such as population growth, the expansion of built-up areas, and changes in land use and land cover, as well as their impact on the environment.

By means of its range of techniques and methods, GIS can provide accurate and up-to-date information about the territory, its resources and its inhabitants, enabling decision-makers to make informed decisions about resource management and development planning. As these technologies continue to evolve and improve, they will play an increasingly important role in shaping the future of spatial development.

Over the last twenty years, geographic information systems and remote sensing have proven to be an excellent way to investigate urban areas. Nowadays, GIS and Remote Sensing technology provide accessible and increasingly user-friendly datasets and data analysis that facilitate integrated spatial information investigation (Gatrell et al., 2007).

Filip (2009) highlights the importance and increased usefulness of geographic information systems in combination with remote sensing in urban system studies. The author emphasizes the technology's contribution to the process of understanding spatial relationships, the ability to update data regularly or in real-time, the production of cartographic materials, and its significance in urban planning and decision-making.

Practically, GIS technology and remote sensing can be implemented and used in all main stages of spatial planning, such as: resource inventory, analysis of the existing situation, modelling and projection (forecasts and scenarios), development of planning options (land suitability analyses), selection of planning options, plan implementation, monitoring and feedback (Yeh, 1999). Combining GIS technology with remote sensing is frequently used to analyze spatial development and identify suitable locations for further development.

According to a report published by NASA, advances in mapping the Earth's surface based on satellite imagery are contributing to a better understanding of the forces behind urban growth and expansion, as well as land management issues. Nowadays, physical expansions such as urban growth patterns and their effect on landscapes can be distinguished, mapped and analyzed using remotely sensed data (Bhatta, 2010).

Although it faces challenges due to various factors, such as the spatial and spectral heterogeneity of urban environments, remote sensing is a suitable source of data for urban studies (Roberts and Herold 2004). Consequently, data retrieved by satellite or aerial remote sensing are increasingly used in spatial analysis and mapping applications of urban areas (Cihlar 2000; Barnsley and Barr 2000; Franklin and Wulder 2002; Zhou et al. 2008; Griffiths et al. 2010; Yang 2011; Qin et al. 2013; Ban et al. 2014), as well as in land cover classification (Yuan et al., 2005; Furberg and Ban, 2012; Wang et al., 2012; Liu, 2015; Haas and Ban, 2018).

Remote sensing can provide spatial planners with crucial data, such as the spatial extent of built-up areas and their multi-temporal dynamics, the spatial distribution of different land use and land cover types, spatial infrastructure and transport networks, and the ability to monitor LULC changes over time (Obade, 2007). According to the same author, monitoring spatial development involves two key aspects: *1) detecting land use/land cover changes* and 2) *analyzing the impact of changes*.

Modelling and multi-temporal analysis of geographical features in a given territory require the creation of robust databases. As mentioned above, the use of remotely sensed data in GIS is crucial to conduct appropriate scientific analyses. Relevant information is often extracted from remotely sensed images through a combination of image classification and change detection methods and techniques.

Many methods have been used to model land cover change, with the aim of identifying factors that affect land conversions, especially between built and unbuilt land cover categories. Multiple multi-temporal images can provide valuable insights into urban growth patterns and the likely factors driving change. However, the quality and availability of data significantly affect the description and modeling of spatial systems (Tayyebi et al., 2010). As discussed above, the spatial dependence of LULC changes can be analyzed by integrating GIS methods and techniques with remotely sensed data in simple or complex analyses and modeling, which provide an effective capacity for spatial assessment and monitoring of urban sprawl.

Methodologies for modelling transitional potential and anticipating potential LULC changes under the effect of geographical variables aim to identify the locations of changes that have occurred and those that may occur in the future. Most of these models examine LULC transitions using multi-temporal LULC data which, when integrated and modelled in GIS, can forecast and simulate future situations (Halmy et al., 2015).

Over time, numerous spatially explicit models have been proposed and used by researchers to analyze and forecast LULC changes, but *neural network-based* models are the most popular for LULC simulation because they accurately reflect the probabilistic spatial nonlinear transformation of land use (Li et al, 2017). Cellular Automata (*CA*) models are widely applied in geography and related fields due to four main advantages: spatiality and affinity with GIS, dynamism, micro-simulation, and a bottom-up approach. Another frequently and widely used model (Urban and Wallin, 2017) for analyzing and forecasting LULC class transitions is the Markov model, which is also used in combination with machine learning tools such as artificial neural networks (ANN-Markov). Cellular automata and the Markov or CA-Markov model belong to the category of cellular models (CM), which operate on the basis of arrays of cells (GRIDs).

These models are deterministic because they model the evolution of variables using logical instructions determined from a grid of cells, each representing a particular class or value. They are based on a set of previously determined rules that define the transition probabilities between different types of classes based on various factors such as proximity to urban centers, accessibility and environmental conditions (Batty et al., 2005, 2007, 2009). Generally, these models have four basic elements: a matrix of cells, a set of characteristics associated with the cells, a neighborhood (cells) defined by the matrix, and a set of transition rules for each cell. Many models also add time as a fifth element (Silva and Clarke 2005).

Based on the discussion above, it can be concluded that geographic information systems and remote sensing are effective tools for monitoring, assessing, and modeling spatial development - understood and evaluated in this research through the lens of built-up area dynamics and multi-temporal land cover change (LULC) by collection, processing, and analysis of spatial information. It is also important to note that practical and theoretical approaches based on the use of GIS and Remote Sensing, combined with statistical data and data collected from the field, are the most advanced and recommended practices for assessing, managing, planning, and forecasting changes in a territory, whether at the local, regional, or global level (Dolean et al., 2020).

CHAPTER 2 - STUDY AREA

The focus of this thesis is on the Cluj-Napoca Metropolitan Area (CMA), as well as the Functional Urban Area (FUA) of Cluj-Napoca municipality, as defined and delimited by the European Commission specialists, within the Urban Audit initiative (2004-2018), based on the ESPON methodology. The area was selected due to its significant urbanization over the past 15-20 years, resulting in a substantial increase in population. This area is of great socio-economic importance and presents a real challenge in terms of territorial planning and development.

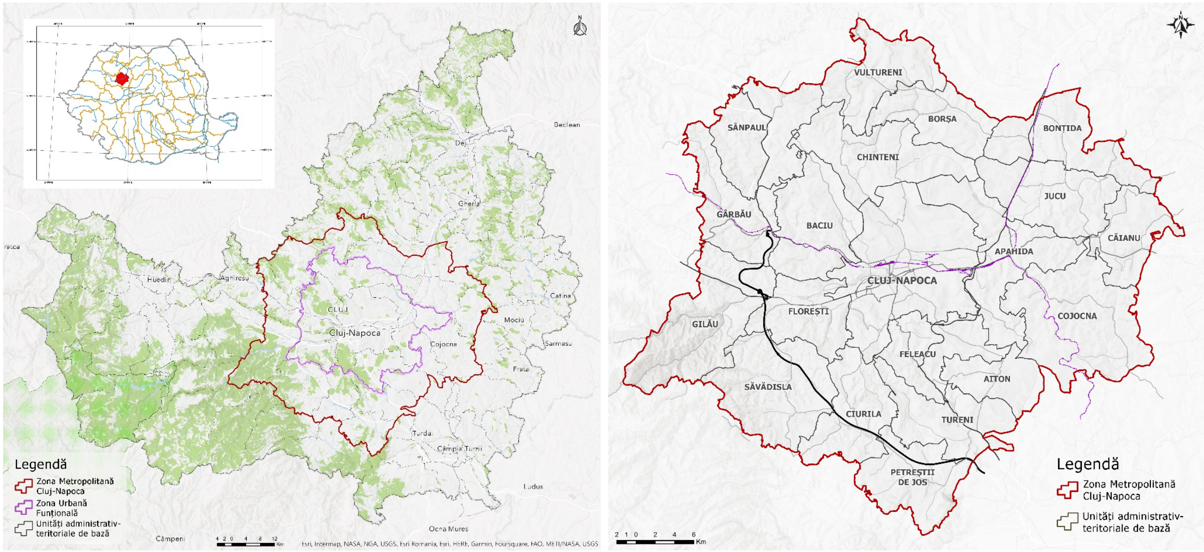


Figure 1. Location and administrative composition of the study area
Data source: ANCPI - TopRo50k (2020)

The Cluj-Napoca Metropolitan Area is among the five existing metropolitan areas in the North-West development region and is one of the largest metropolitan areas in Romania. Since its establishment in 2008, the CMA has undergone changes in terms of its administrative-territorial units (TAUs). At present, it consists of the Cluj-Napoca municipality and the following municipalities: Aiton, Apahida, Baciu, Bonțida, Borșa, Căianu, Chinteni, Ciurila, Cojocna, Feleacu, Florești, Gârbău, Gilău, Jucu, Petreștii de Jos, Săvădisla, Sânpaul, Tureni, and Vultureni.

The 20 municipalities that comprise the CMA cover an area of more than 1,828.72 km², which represents 27% of the total area of Cluj County. These municipalities are home to 454,576 inhabitants, which accounts for 54.47% of the county's population. The population density in the metropolitan area is thus over 248 inhabitants/km², compared to only 60 inhabitants/km² in the rest of the county, underscoring the significant polarizing effect of the Cluj-Napoca municipality within the county territory (SIDU Cluj-Napoca, 2021).

As previously mentioned, the CMA is situated within Cluj County, which is one of the most rapidly expanding economic regions in Romania. The administrative-territorial unit's per capita GDP has shown significant yearly increases, rising from 31% of the EU average in 2000 to around 70% in 2015. This trend continued in subsequent years, and by 2020, it reached 103% of the EU27 average (Eurostat). Between 1990 and 2021, over 88,000 new housing units were constructed in Cluj County, a feat surpassed nationally only by Bucharest municipality and Ilfov County. It's important to note that much of this new development has occurred in peri-urban areas and often in an unstructured and disorganized manner.

At European level, Cluj-Napoca and its metropolitan area is the most important urban center in the perimeter delimited by the capitals Bucharest, Belgrade, Budapest, Kiev and Chișinău. This context gives it the opportunity to become a transnational *hub* of Central and Eastern Europe (SIDU Cluj-Napoca, 2021). The latest Eurostat data indicate that the CMA is the fastest growing economic area in the European Union (EU) between 2000 and 2019, a pace that has been maintained in subsequent years. It is also important to note that despite the performance recorded in terms of gross domestic product in the period under analysis, the growth rate has also caused a number of negative externalities - chaotic urban development and *urban sprawl*, congestion, pollution, rising prices and cost of living (SIDU Cluj-Napoca, 2021).

Urban planning and development in Cluj-Napoca and its metropolitan area present a unique set of challenges that are faced by many of Romania's larger cities. The municipality's initially dense development pattern was partly due to its topography, which caused a narrowing of the valley corridor in the contact sector of the Nadăș-Someșul Mic watershed and the northern extension of the Feleac Hill. However, over the last decade, development in the area has been characterized by a decrease in density in central areas and a significant increase in density in certain peri-urban areas.

An examination of the socio-economic aspects (which are part of the anthropogenic subsystem) at the level of the CMA reveals an interdependent link between the evolution of the population, real estate development, and economic growth, all of which significantly impact territorial development. Over an analyzed period of almost 20 years (2002-2021), the population of the CMA increased by a little more than 61,000 people, while in the rest of Cluj County, it decreased by more than 41,000 people, indicating a growing trend of population migration to Cluj County and concentration in the metropolitan area.

CHAPTER 3 - METHODOLOGY AND DATA

In this PhD thesis, a theoretical framework of reference was outlined and appropriate methodological approaches were defined and adapted for both theoretical and practical (applied) parts. Research methods were chosen based on the main objectives of the scientific approach, which involved theoretical grounding and consultation of literature, as well as the development of models and analyses to obtain and validate results, and draw conclusions. This chapter provides a description of the types of analyses conducted, their main assumptions, techniques, methods, and data used in the practical part of the study.

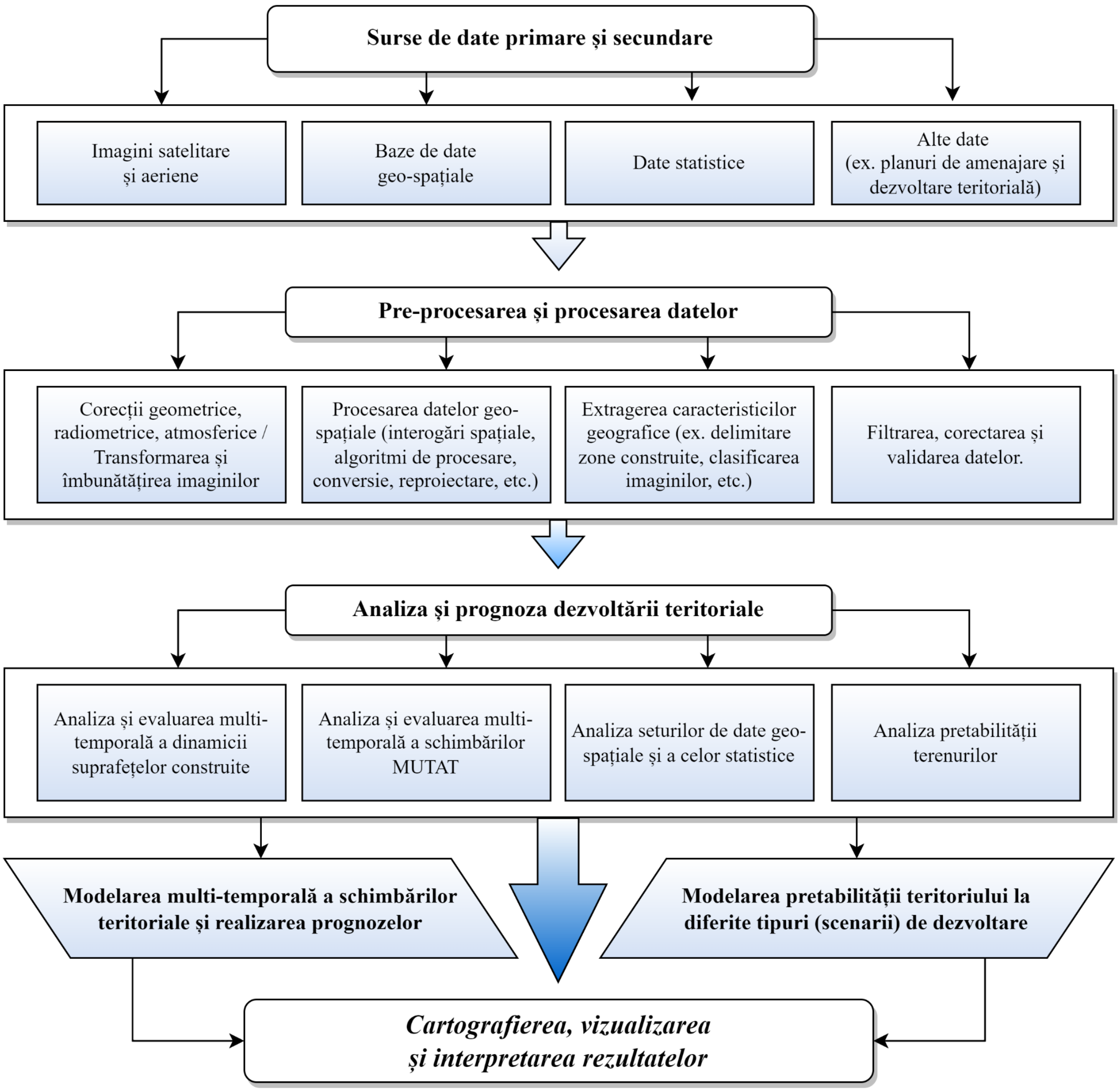


Figure 2. Components and logical structure of the methodological-applicative approach

The development of application support from a methodological perspective relies on implementing GIS technology and remote sensing data to model and evaluate geographical features that reflect territorial development. To achieve this, a broad range of complex analysis and forecasting methods and techniques have been employed, and the results have been visually represented using cartographic methods. The final phase of the research involves formulating conclusions based on the outcomes, which is accomplished through analysis and synthesis.

The practical-applicative approach can be segmented into three main sections:

1) **Delineation and multi-temporal analysis of built-up area expansion** (urbanization or urban growth) - level 2 of abstraction, which first involved the use of a proprietary methodology (Dolean et al. 2020) to delineate and extract built-up areas at different reference time points (2000, 2005, 2010, 2015, 2020), based on a semi-automated spectral index application approach using Landsat TM and ETM+ medium resolution satellite imagery. Secondly, the analysis aimed, on the one hand, at assessing the dynamics of built-up areas based on available European and/or national geospatial datasets and, on the other hand, at correcting and validating the results obtained using existing geospatial data and medium-high and high-resolution satellite imagery, Sentinel (10m), RapidEye (5m) and PlanetScope (3.25m) respectively. The spatial datasets used in this phase were mainly those provided by the European Space Agency (ESA) through the Copernicus programme - Land Monitoring Service - High Resolution Layers. In this phase, the analysis was carried out at the whole CMA level and the results obtained were correlated with statistical data and spatially distributed data in the form of GRIDs on population and economic activities.

2) **Analysis and forecasting of multi-temporal spatial change** (including land use and land cover) - level 1 of abstraction; mainly involving a more detailed view of spatial development in relation to land use/land cover dynamics.

Due to the targeted level of detail and the availability of data, this analytical part has been carried out in a disaggregated manner regarding the studied territory. As a consequence, some of the applications were focused on the whole territory of the Cluj-Napoca Metropolitan Area, while others were limited to the territory of the Cluj-Napoca Functional Urban Area (the first ring of the CMA). The rationale for this approach is justified, on the one hand, by the fact that most of the changes both in terms of built-up areas and socio-economic factors took place in this area. In addition to the above, there are considerations related to data availability and computational processing difficulties.

The hybrid approach was also used in this phase where on the one hand LULC class data obtained by supervised pixel-based classification of Landsat satellite imagery and object-based classification by segmenting high-resolution satellite imagery (RapidEye, PlanetScope) were used, and on the other hand spatial datasets with a high level of granularity (Urban Atlas 2005-2018, APIA data 2006-2020) were used in combination with aerial imagery used for correction, updating and validation of results. The main aim of this step was to have a dataset with the highest accuracy representing the main land use/land cover classes for each reference year concerned.

Subsequently, the results obtained were used in the assessment of territorial changes using GIS spatial analysis methods in combination with change detection techniques and forecasting based on spatially distributed dynamic models - Cellular Automata and Markov model in combination with artificial neural networks.

The second level of abstraction mentioned earlier entails modeling spatial development as a multi-temporal process by examining the relationship between built-up areas (artificial or impermeable) and unbuilt-up, natural, or permeable areas. In contrast, Level 1 abstraction entails a more detailed modeling of spatial development by analyzing land cover and/or land use dynamics.

3) **Analysis of land suitability for different development scenarios** - covering the entire metropolitan area, applied at the parcel or group of parcels level, based on algorithms developed by the author in collaboration with World Bank urban development specialists. The developed methodology has been tested and validated in professional practice by implementation in regions similar to the study area (e.g., Brno MA in the Czech Republic and Rzeszów FUA in Poland) and is constantly adapted and improved according to the available data and the results obtained. The methodology actually involves the use of deterministic models for assessing the suitability of trains for various development scenarios with the aim of serving as a tool for coordination and planning of spatial development by decision-makers based on empirically determined fundamentals. Each scenario analyzed involves the use of a variable number of parameters considered relevant, and for each parameter a series of metrics and associated scores are defined. The final suitability is obtained at the level of the analyzed spatial entity (e.g., parcel) by calculating the weighted contribution of each score obtained by each parameter.

It is important to note that the multi-criteria land suitability analysis methodology is particularly flexible - the parameters, value classes and scores used, as well as the weight in the final result can be modified and adapted according to the size and specificity of the analyzed area, the availability of data or other specific conditions. The current approach adopts the presented and applied methodological version as a proposal and example of how to determine the suitability of land. The parameters, value classes, and weights used were determined based on the author's experience and knowledge of the analyzed territory.

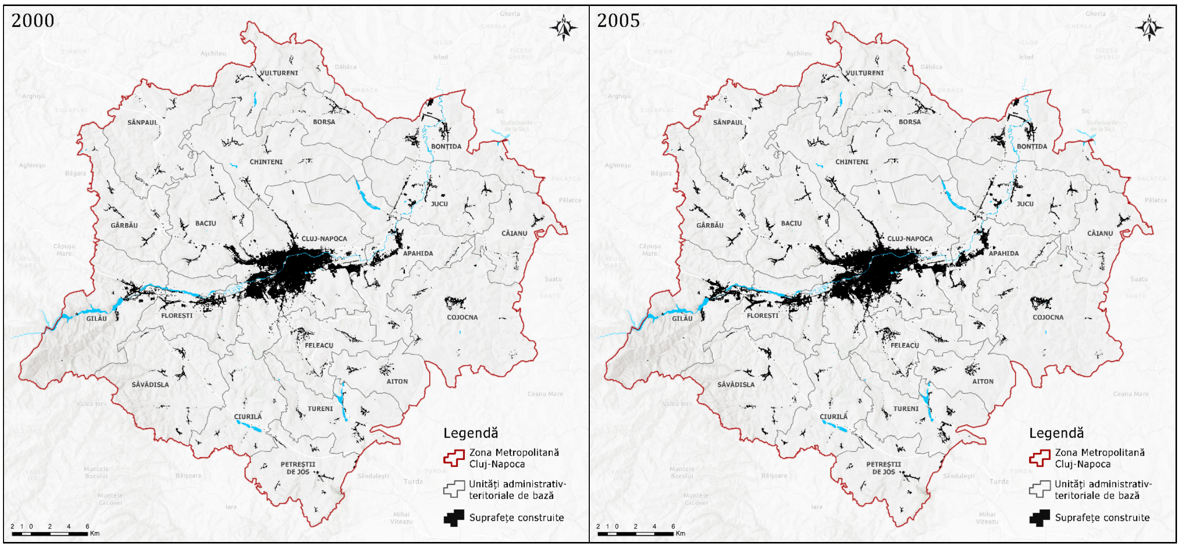
Well-founded research necessitates a comprehensive and accurate database that is closely related to the subject of study. One of the principal benefits of GIS technology is its interoperability and capacity to integrate and analyze vast amounts of data from diverse sources.

Consequently, the source and quality of the data used in the applications is indispensable for the accuracy and reliability of the results. A particularly important part of the study was concerned with the integration, processing and management of spatial data. The database generated and used in this research can be grouped into three main categories: *geospatial data*, *remotely sensed data* and *statistical data*. It is important to note that remotely sensed data play a crucial role in the analysis of spatial development, urban growth and land use dynamics by integrating them into spatial GIS analysis. Therefore, in the analytical approach, in addition to geospatial and statistical databases extracted from various sources, numerous satellite and aerial images with different spatial resolutions were used. All satellite images used were subjected to geometric, radiometric and atmospheric corrections.

CHAPTER 4 - RESULTS AND DISCUSSION

This chapter provides a brief presentation of the primary research findings by providing an outline of the progress of built-up areas and territorial changes over the previous two decades, their present status, and potential future development trends.

The application of the methodology for delineating and mapping built-up areas based on the implementation of spectral indicators was achieved by analyzing Landsat medium resolution (30m) satellite images at five reference time points covering a 20-year horizon. Consequently, built-up areas were identified and delimited for the reference years 2000, 2005, 2010, 2015 and 2020 for the entire Metropolitan Area of Cluj-Napoca.



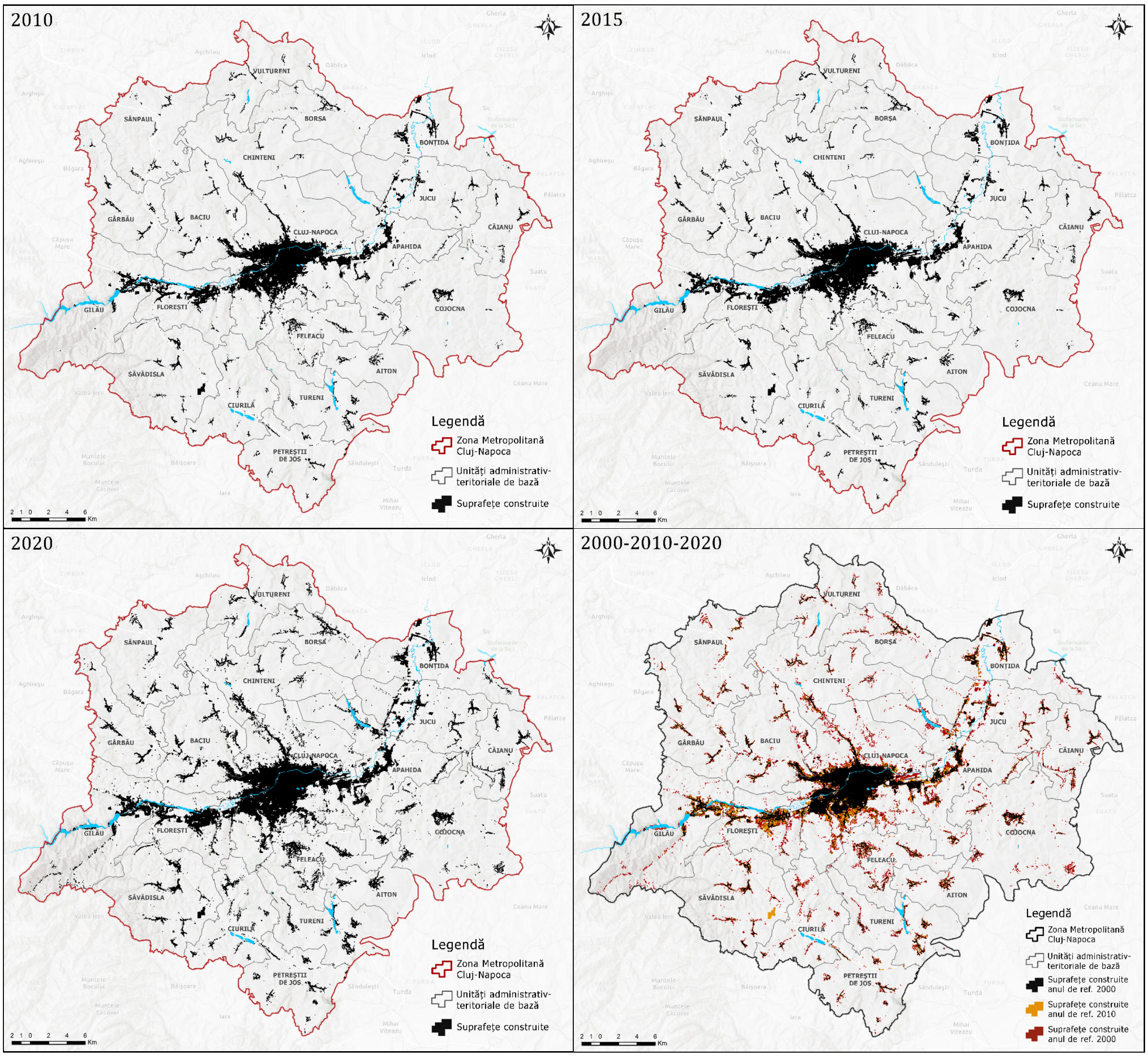


Figure 3. Built-up areas at CMA level between 2000-2020

To evaluate the performance of the proposed methodology and validate the results, several quantitative and qualitative methods commonly used in remote sensing were employed. The first method used to assess the accuracy of the model was the traditional *confusion matrix*, or error matrix. The overall accuracy of the methodology applied in the study area, at the level of all the reference years analyzed, was generally above 85%. This can be considered a very good result, especially taking into account the high degree of heterogeneity of the analyzed territory. Also, the average value of the Kappa coefficient shows very good values (above 0.80 for each time point evaluated) which is in the range 0.61 - 0.99 corresponding to a substantial to almost perfect agreement between the results obtained and the reality on the ground, defining the high degree of performance of the evaluation as opposed to the possibility of obtaining agreements in a random way.

The second method of assessment and validation involved creating a comprehensive database containing the footprint or GPS coordinates of a large number of existing buildings at the end of the reference year interval. Due to the fact that on the basis of this validation method, the samples used represent the actual field locations of the buildings, as expected, the results were considerably better than for the method presented above (average overall accuracy of more than 90%).

The third validation method involved a direct comparison between the values representing the area of built-up land obtained by the proposed methodology, i.e., by supervised classification of satellite images, and the values obtained by similar delineation methods - databases from independent sources or provided by competent institutions in the field, or statistical data from official sources. It is worth noting that, despite quantitative errors - differences between the actual areas on the ground and those defined on the basis of the methodology - the overall multi-temporal trend of the expansion of built-up areas was rendered with a very high accuracy of over 90%, which makes the assessment of the spatial dynamics of built-up areas by reference to the percentage rate of change (both from one reference point to another and for the entire period under analysis) particularly relevant and accurate.

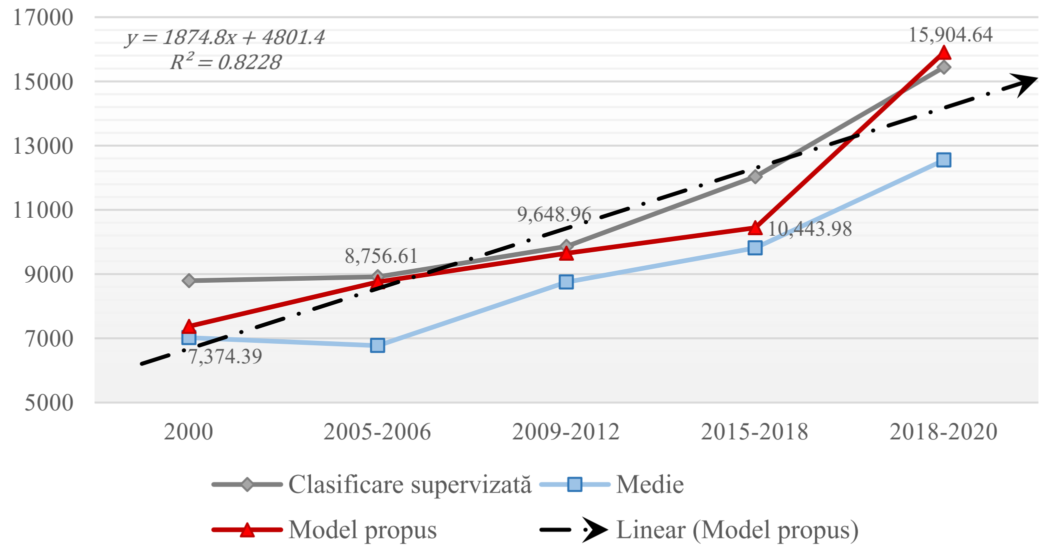


Figure 4. Comparison of different quantitative methods for assessing model accuracy

The results illustrate that the applied and evaluated method is a relatively accurate and, at the same time, reliable option for rapid (semi-automated) mapping of built-up areas. It is also noted that, compared to the use of traditional spectral indicators for differentiating built-up areas, the applied method succeeds in highlighting and delineating built-up areas with a higher accuracy and a lower degree of error - especially in terms of reducing the degree of spectral confusion between different land cover class characteristics. This can be particularly useful and with important potential applications, especially in the field of spatial planning and regional development.

The assessment of the multi-temporal spatial dynamics of built-up areas in the study area was based both on the results obtained from the application of the built-up area delineation model presented above and on the alternative source datasets used to validate the model.

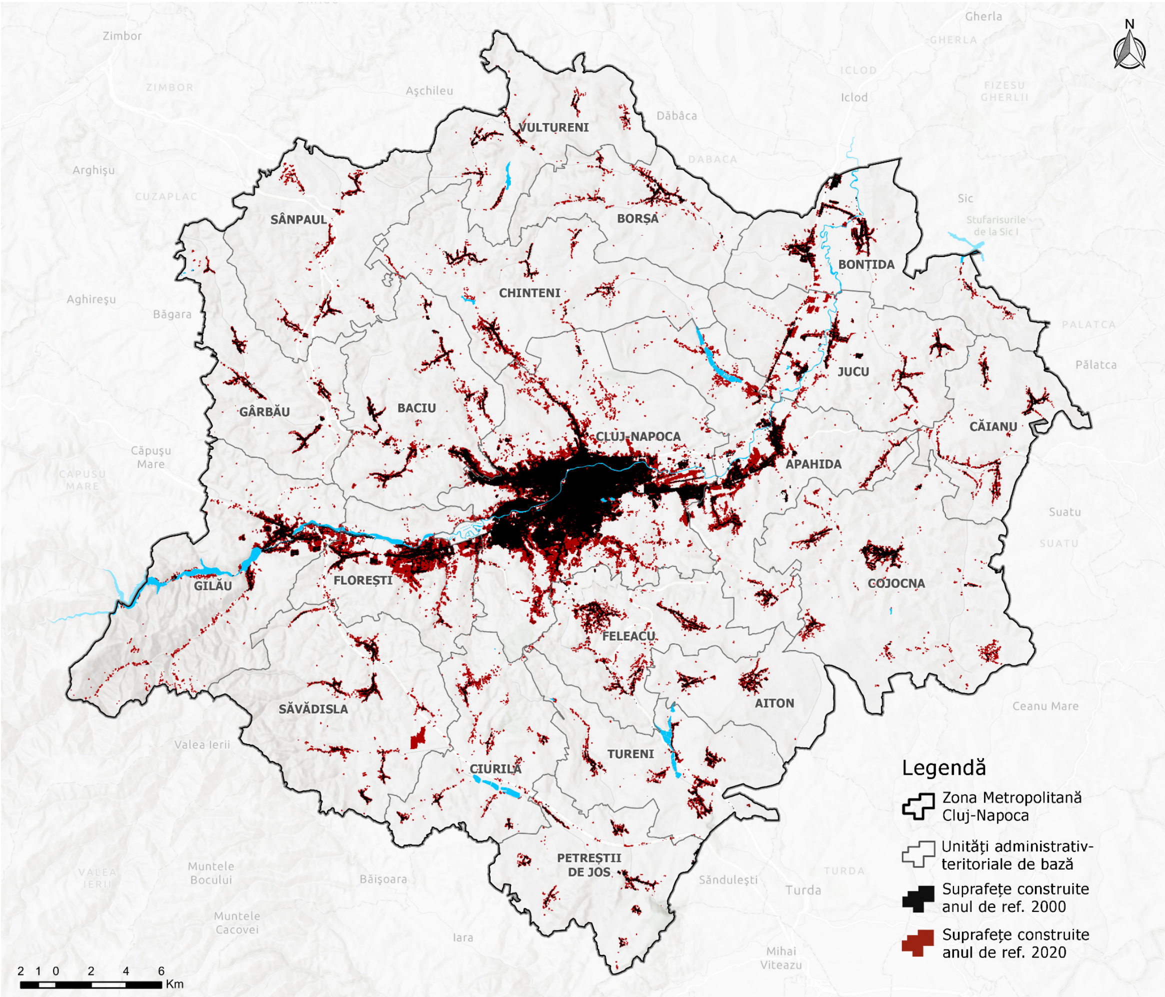


Figura 5. Expansion of built-up areas in CMA between 2000 and 2020

The results showed that the built-up area of the CMA doubled between 2000 and 2020, i.e., in 2000 the built-up area amounted to 7374.39 ha, representing 4.237% of the total area of the CMA, while in 2020 the built-up area reached 15904.64 ha, representing 9.138% of the total CMA, thus registering a total growth rate of 115.67%. As regards the spatial distribution of the expansion, a massive increase in the built-up areas can be noticed in the administrative units on Someșul Mic Corridor, along the main east-west development axis of the CMA (Jucu, Apahida, Cluj-Napoca, Florești, Gilău). At the same time, an impressive increase can also be noticed on the secondary north-south development axis, especially in the localities in the immediate vicinity of Cluj-Napoca (Baciu, Chinteni, Feleacu, Ciurila, Tureni).

The trend of development in bands in the metropolitan area is therefore reconfirmed, thus showing two rings in terms of density dynamics and proximity to the urban center with a polarizing function: the first ring, consisting mainly of the communes of Apahida, Feleacu, Florești, Baciu and Chinteni, characterized by high and very high increase in built-up areas in relation to the entire CMA, and the second ring, characterized, with some exceptions (Jucu and Gilău), by medium and low increase in built-up areas in relation to the entire analyzed territory.

The quantitative analysis of the evolution of the built-up areas at the level of the TAU components of the Cluj-Napoca FUA shows that, in 2020, more than 60% of the total built-up areas at the level of the CMA were concentrated in the TAUs of the first ring, despite the fact that they represent cumulatively less than 30% of the total territory of the CMA. Inversely calculated, a share of less than 40% of the total built stock at the CMA level is distributed in more than 70% of the territory.

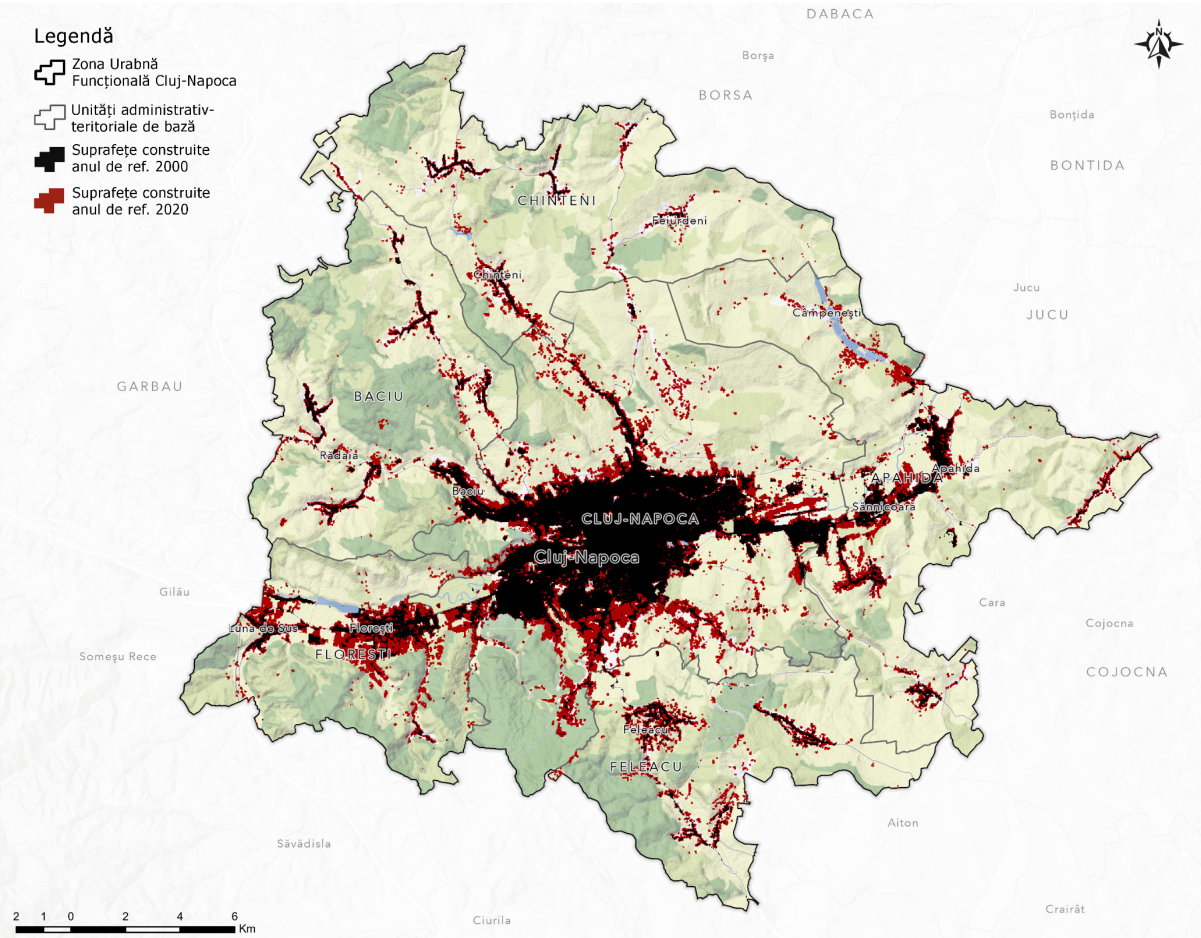


Figure 6. Expansion of built-up areas at Cluj-Napoca FUA level between 2000 and 2020

Also, according to the analyses carried out, the projected development prospects for the next 5-10 years follow the same upward trend, which requires careful monitoring of sensitive areas in terms of urban planning and, where appropriate, the swift implementation of directive measures to ensure sustainable local and regional development.

The development of forecast scenarios for the spatial expansion of built-up areas at the MCA level involved the implementation of a relatively simplified ANN-CA spatial distributed model. The model, which is most often used for the predictive representation and simulation of spatiotemporal transitions between major LULC classes, involves the use of Cellular Automata (CA) in combination with machine learning algorithms - Artificial Neural Networks (ANN) and Multilayer Perceptron (MLP), to determine, in a dynamic way, the transition potential of the targeted geographical features, based on a set of user-defined spatial variables.

In this case, the ANN-CA model was applied with the main input data being the built-up areas delimited on the basis of Landsat satellite images for the years 2000 (time t_0) and 2020 (time t_2). By implementing the model, two forecasting scenarios were developed for the reference years 2025 (time $t_{2+0.5}$) and 2030 (time t_{2+1}). In order to validate the model, an intermediate variant was also carried out, involving the development of a forecast scenario for the year 2020, using as input data the existing built-up areas in 2000 (time t_0) and 2010 (time t_1), the result being compared with the actual situation in 2020, obtaining an overall accuracy of 78.3% and a Kappa coefficient value of 0.88.

The values obtained in the validation process can be considered very good, especially in the context that the rate of growth of built-up areas in the period 2000-2010 was considerably lower than in the period 2010-2020, which is impossible to capture in predictive modelling.

The projected expansion of built-up areas for the 2025-2030 horizon mainly maintains its upward trend and multi-annual growth rate, having a very close correlation in absolute terms with the average growth values over the 2000-2020 period - a situation that can be explained, of course, by the fact that the forecast scenarios were generated on the basis of previous transitions in the specified period.

Modelling, assessment and predictive simulation of spatial change, through multi-temporal analysis of land use and land cover transitions, falls under abstraction level 1 in terms of the spatial manifestation of territorial development. It aims to determine a more detailed view of multi-temporal spatial dynamics by relating it to the main land use and land cover classes as opposed to simply analyzing, in generalized form, the artificial (built) - natural (unbuilt) dichotomous relationship.

In this regard, the classification of satellite images was used to obtain thematic layers on the land cover/land use status of the reference year in order to be used in the analysis, modelling and prediction of transitions between classes. The classification of the satellite images in the database was performed using two distinct approaches. The first approach involved supervised pixel-oriented classification of Landsat satellite images (MLC algorithm), focusing on the reference years at the beginning and the end of the analyzed time period (2000 and 2020) respectively.

The second approach aimed at using the latest object-oriented classification methods and techniques (OBIA or GEOBIA, based on the Support Vector Machine - SVM classifier) by segmenting RapidEye (2012, 2018) and PlanetScope (2020) high-resolution satellite images. This operation was also mainly focused on the reference years at the beginning and end of the period under analysis, taking into account, of course, data availability (2012-2020). Given the quality and resolution of the satellite images used, as well as the classification methods employed, the results obtained were considerably better than Landsat satellite images, with a higher degree of accuracy and detail.

The assessment of classification accuracy is an elementary step in the classification procedure of remotely sensed images. To this end, classification accuracy was assessed using confusion metrics based on a sample of 1,000 validation points for each class evaluated. The results of the accuracy assessment procedure for all the analyzed satellite images yielded very good results in terms of overall accuracy, above 80%, despite the fact that the accuracy variations between the assessed LULC classes were recorded in this process.

It is worth noting that the object-oriented classification using SVM resulted in higher accuracy compared to the traditional pixel-based classification using MLC, which was expected. Therefore, it can be concluded that pixel-oriented analysis using MLC is more appropriate for classifying medium resolution Landsat satellite images, while object-oriented analysis is more suitable for classifying high resolution satellite images such as RapidEye and PlanetScope. This is because the higher level of image detail in high resolution satellite images allows for distinguishing textures and shapes, which, when combined with the spectral response of the surfaces, enables very high accuracy classifications.

The qualitative and quantitative analysis of changes in the study area shows a significant increase in built (artificial) areas at the expense of semi-natural areas, which was previously highlighted and explained in the evaluation of the expansion of built areas. Consequently, over the last 20 years, urbanization has resulted in an excessive conversion of semi-natural areas and arable land into built-up areas.

As previously noted in the analysis of urban growth, the built-up area of the metropolitan area almost doubled over the analyzed time period. In the year 2000, the built-up area had represented approximately 4.7% of the total area, whereas by the year 2020, it reached an impressive 8.2% of the total area. The extensions were mainly located on Someșul Mic

Corridor, along the east-west development axis, but also along the north-south development axis in the municipalities in the immediate vicinity of Cluj-Napoca.

During the expansion of built-up areas, there has been a decline in the areas of arable and semi-natural land, resulting in their share of the total area decreasing by 1.4% and 2%, respectively. An interesting aspect that can be noticed regarding the transition of arable land is that, despite the massive reduction of areas in favor of built-up areas in the communes along the Someşul Mic corridor, there was also a notable increase in the administrative-territorial units with fertile land in the second ring of the CMA, particularly in the communes located in the southeast and northeast of the territory.

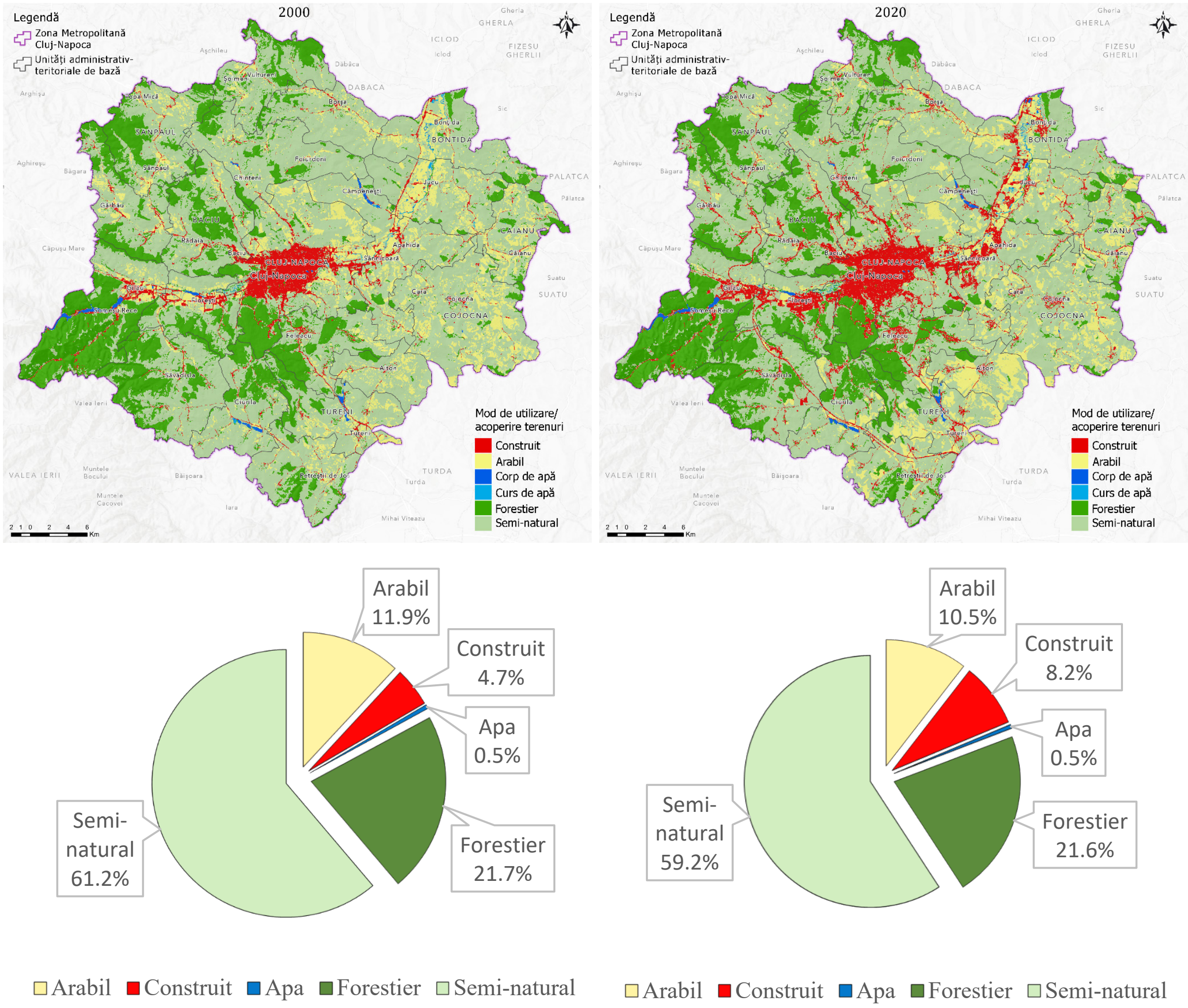


Figure 7. Spatial distribution and structure of LULC classes resulting from Landsat satellite image classification (2000-2020)

The quantitative and qualitative assessment of the changes in land use and land cover in the last 15 years at the level of the Cluj-Napoca FUA, based on the Copernicus-Urban Atlas datasets, shows, with small exceptions, massive expansions of the urban fabric. One notices that these expansions were mainly achieved by „devouring” agricultural and semi-natural land, combined with a densification of areas characterized by medium and low-density urban fabric.

In line with the procedure for assessing changes in land cover and land use resulting from spatial development over the last two decades (2000-2020), the forecast scenarios for the 2025-2030 period were also developed on the basis of two approaches, using the same two final datasets. Thus, forecasting scenarios on potential changes in land use and land cover were produced, both at the level of the metropolitan area - in a somewhat more generalized way - and at the level of the functional urban area, in a more detailed version.

The first variant, carried out for the entire CMA, involved using as input data the thematic layers obtained from the classification of Landsat satellite images (30 m), representing the LULC situation in 2000 (time t_0 - beginning of period) and the situation in 2020 (time t_2 - end of period).

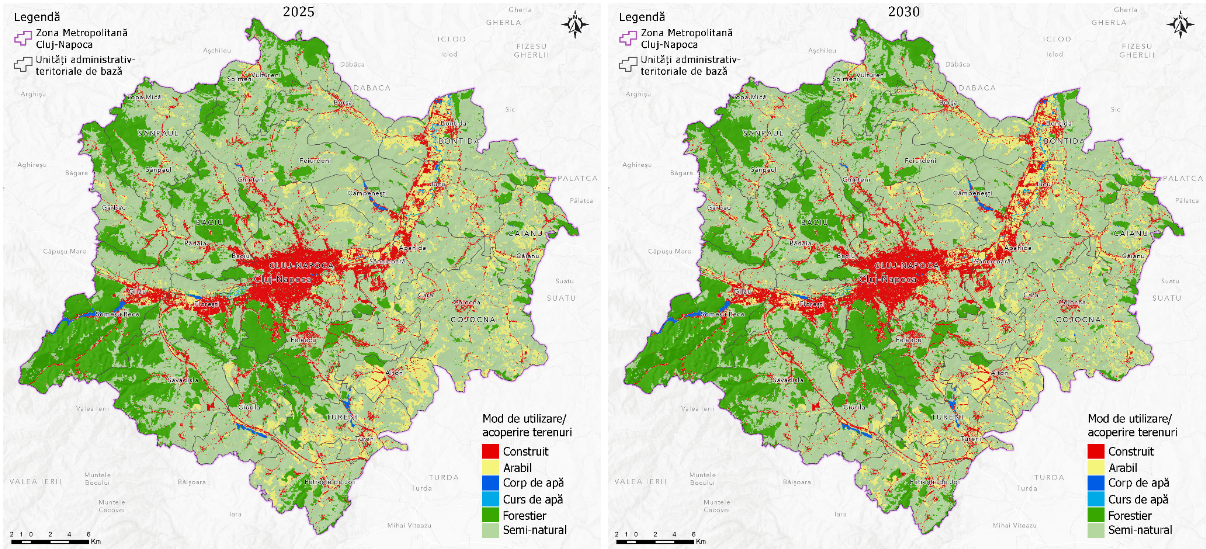


Figure 8. Results of forecasting scenarios carried out at the CMA level (2025-2030)

The second variant, carried out at FUA level, involved the use of thematic layers representing the LULC situation from 2005-2020, resulting from the conversion of vector data from the Copernicus-Urban Atlas set into raster format with a spatial resolution of 5 m. Thus, the LULC situation in 2005 (time t_0 - beginning of period) and the LULC situation in 2020 (time t_2 - end of period) were used as main input data. In both approaches, for model validation, test scenarios were first performed on the basis of the thematic layers related to the LULC situation at intermediate points in time (time t_1 - intermediate period), evaluated on the basis of the actual situation at the end of the period, obtaining in both cases values above 80%-85% in terms of overall accuracy and above 0.85 in terms of Kappa coefficient values.

Finally, by implementing the ANN-Markov model, forecasting scenarios for the reference years 2025 (time $t_{2+0.5}$) and 2030 (time t_{2+1}) were produced, following the recommendation that the forecast horizon should be at most half of the time lag of the input data. The parameters used to determine the transition potential and spatially model future transitions were related to aspects such as topographic land features and proximity relationships.

The selection of variables with considerable relevance in the model was based on assessing spatial correlations using the Cramer V (Cramer's coefficient) method. This method was used to evaluate spatial correlations both between parameters (each with each other) to reduce redundancy and in relation to identified territorial transitions.

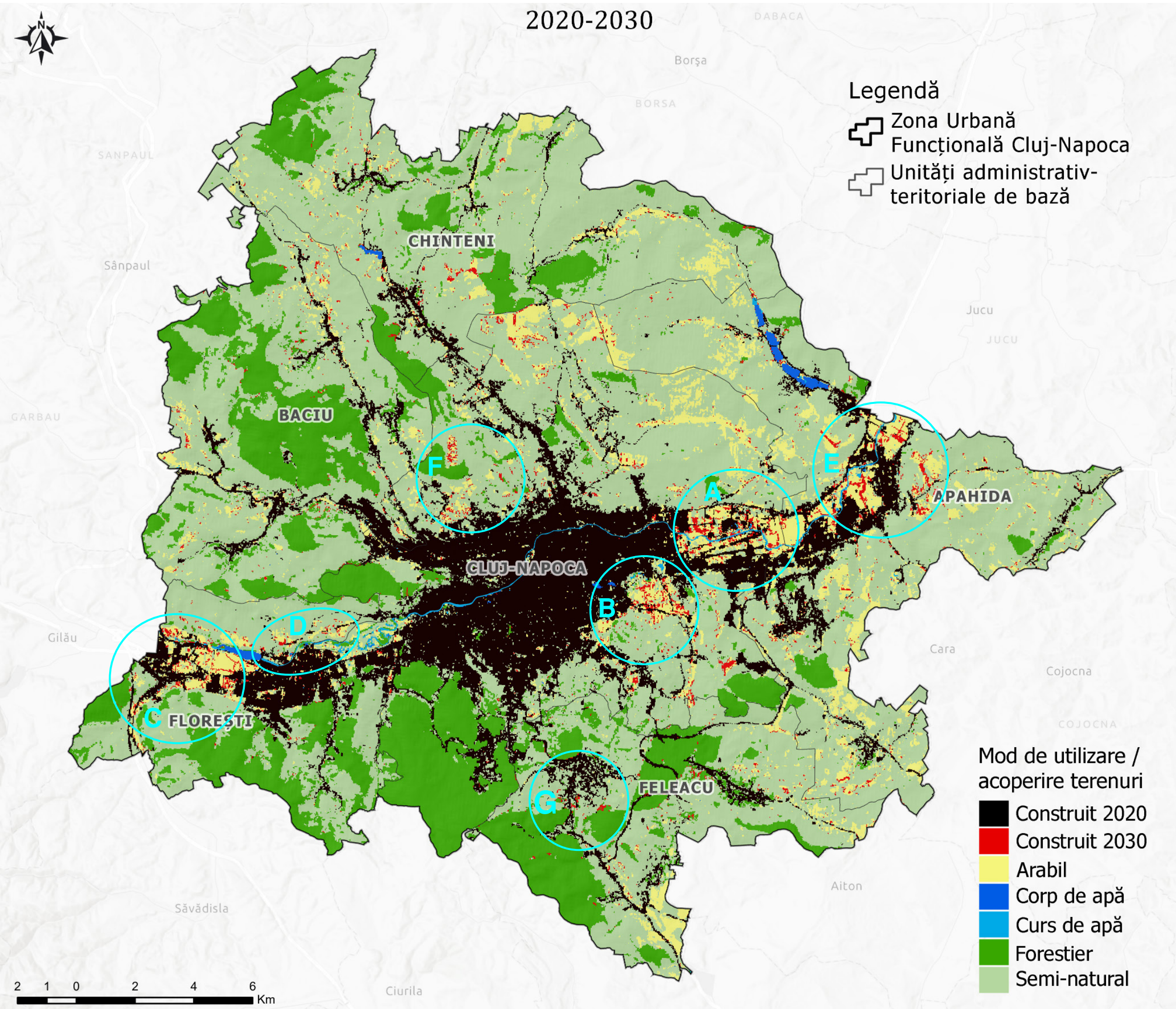


Figure 9. Forecast scenario for the 2030 reference year at the Cluj-Napoca FUA level

The results indicate that the expansion of built-up areas at the expense of natural areas will continue over the forecast time horizon, particularly in units located on the primary development axis of the CMA (east-west), as well as in those in the vicinity of the city on the secondary development axis (north-south). Furthermore, the analysis suggests that accessibility and land availability will have a significant impact on future developments, with much of the projected expansion of built-up areas concentrated along arterial roads leading from the center to the periphery.

The forecasting scenarios suggest that there may be a continuation or increase in pressure on natural areas due to the expansion of built-up areas, especially along the primary development axis. In Cluj-Napoca, the most significant projected expansions of built-up areas are in the Muncii Blvd. and airport areas, as well as the Sopor and Borhanci areas. In terms of the rural territory, the Apahida and Florești communes have the most significant potential expansion of built-up areas, which may negatively impact arable and semi-natural land such as meadows and pastures. A large portion of this new development is forecasted in areas with high suitability and available land, specifically the quasi-flat land in Luna de Sus and the vicinity of the northern belt, including the localities of Sânnicoară, Sub-Coastă, Dezmir, and Apahida.

The determination of land suitability across the metropolitan area was accomplished by utilizing relatively complex methodologies that involved a significant amount of data and various spatial analyses conducted in a GIS environment with a high level of detail. This approach enables the determination of land development potential in a comprehensive manner, at the parcel or group of parcels level.

Regarding development potential, an analysis was conducted in terms of the possible functions that individual plots of land could serve, such as residential, mixed, industrial, commercial, etc. For each of these functions or development types, a multi-criteria evaluation model was developed that integrated a range of relevant parameters, including the degree of accessibility and connection to the territory, the degree of accessibility to technical infrastructure, the spatial distribution of land in relation to central areas, and the size and shape of plots, among others.

The implementation of multi-criteria models that can integrate and analyze large amounts of data objectively based on specific criteria can offer essential support in making informed decisions. The results should be viewed as a tool that necessitates interpretation and should not be considered as the sole determinant of the development vision.

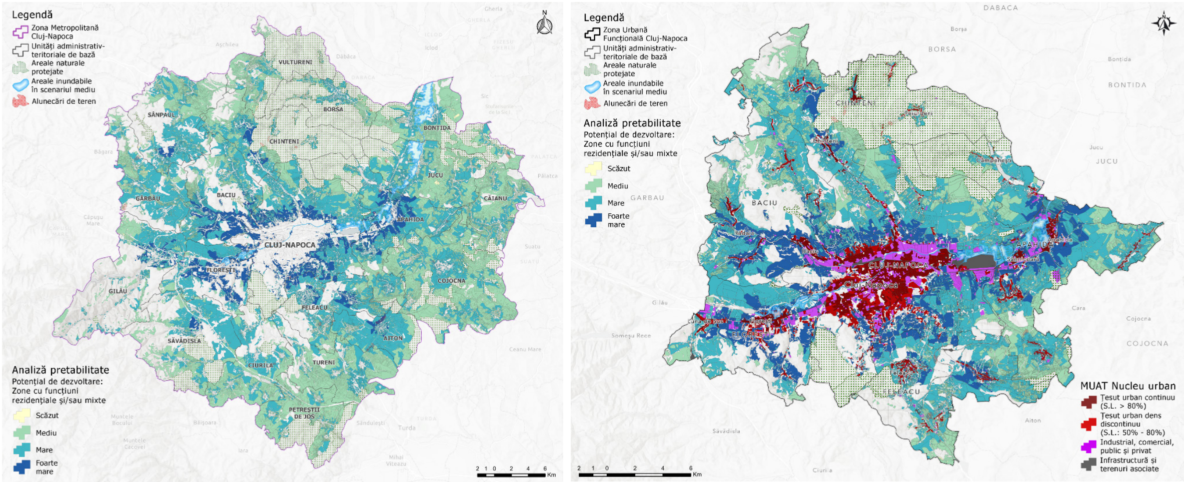


Figure 10. Land development potential for residential and/or mixed-use areas at the CMA and Cluj-Napoca FUA level

The results indicate that the suitability for *residential and/or mixed functions* generally increases from central areas to the suburbs, along the main transport corridors. As a result, land with high and very high development potential is primarily concentrated in areas with high accessibility, particularly land located near the road transport network. Moreover, a significant clustering of land with high and very high potential for this type of development is noticeable within a radius of roughly 15-20 km around the Cluj-Napoca City, specifically within the 30-minute isochrone for road accessibility.

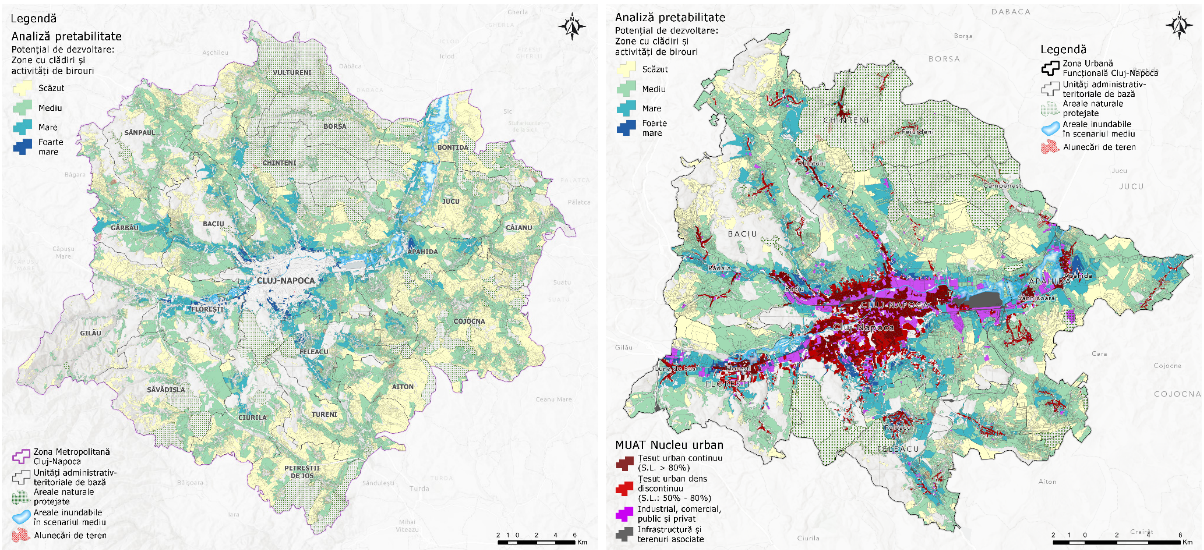


Figure 11. Development potential of land for areas with office buildings and activities, at the level of CMA and Cluj-Napoca FUA.

Within the analyzed territory, *land with high and very high potential for buildings and office space* is mostly found in undeveloped areas of Cluj-Napoca City and in the villages in its immediate vicinity, located along the two development axes (east-west and north-south). The potential of this type of development is highlighted by the fact that the susceptible lands are characterized by an important concentration of population and economic activities, which were also considered in the methodology. Furthermore, based on the criteria used, lands with increased suitability are concentrated in areas with excellent accessibility, both in terms of proximity to the road transport network and public transport.

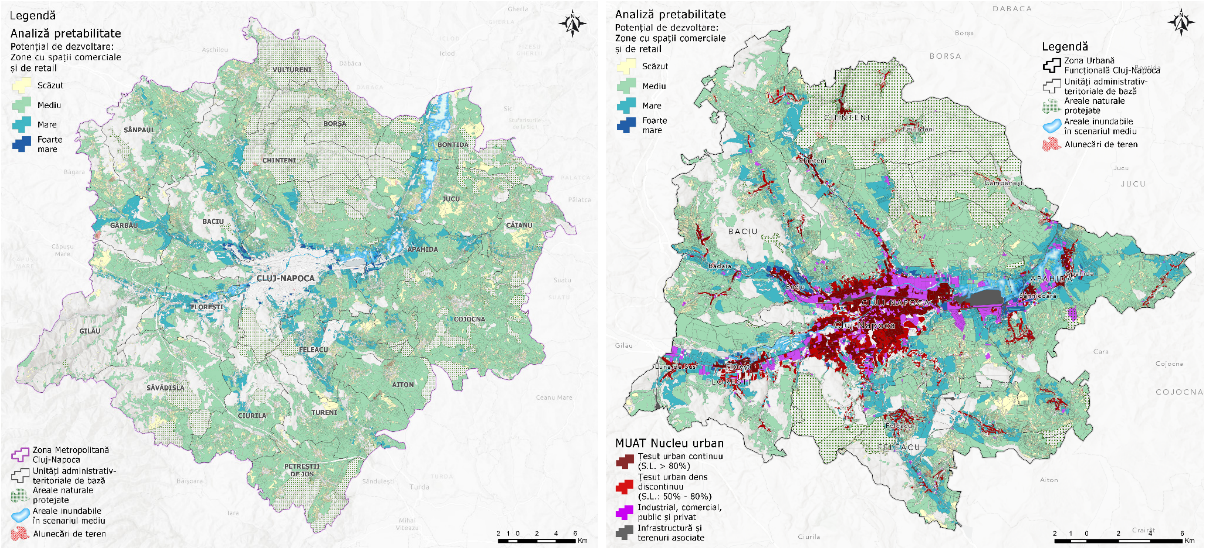


Figure 12. Land development potential for commercial and retail area in the CMA and FUA

The analysis of the *suitability of land for commercial and retail areas* shows a more pronounced potential around the city of Cluj-Napoca, with a stronger concentration in the central areas of the localities on the main development axes of the CMA. Generally, commercial and retail areas are located in densely populated areas with high commercial activities. Not surprisingly, a simple correlation of the results with the gross local income per capita shows a higher concentration of land with high suitability in medium to high income localities (Baciu, Feleacu, Florești) and high-income localities (Apahida, Jucu), gravitating around the city of Cluj-Napoca, where very high incomes are recorded.

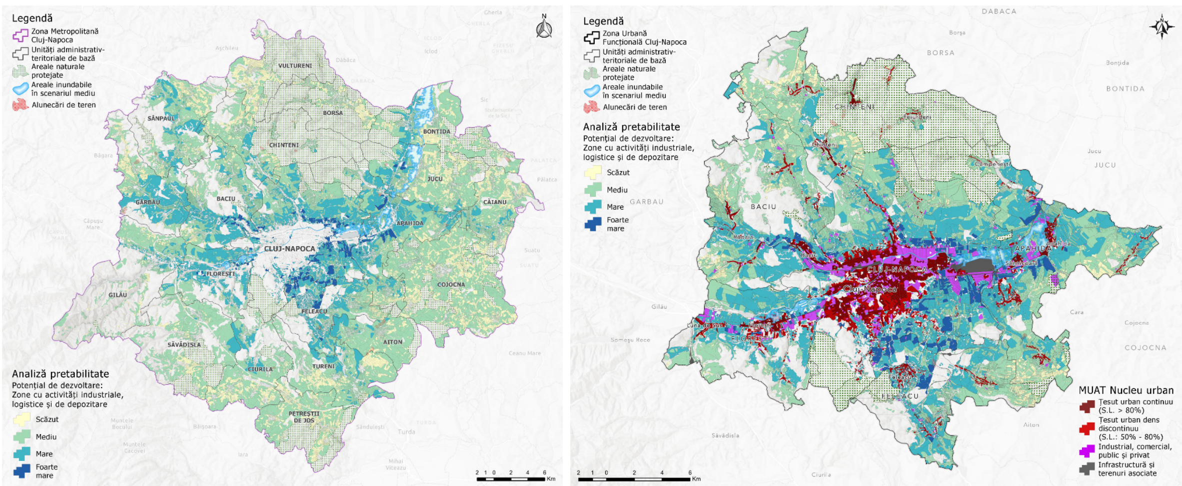


Figure 13. Land development potential for industrial, logistics and warehousing activities at the level of CMA and Cluj-Napoca FUA

There is a significant concentration of areas with *high and very high suitability for industrial, logistic, and warehousing activities* in the immediate vicinity of Cluj-Napoca, particularly in the north-east and south-east regions of the territory. Many of these areas are already recognized for their industrial-logistic potential, as evidenced by the location of numerous industrial, logistic, and warehousing facilities such as those in the north-eastern part of the municipality, specifically in the area of Muncii Blvd. and near the airport, the units in Apahida - especially those in Sânnicoară area, and those in Feleacu-Tureni area. In addition, there is a high degree of land suitability for this type of development in areas in the western proximity of the city, around Florești-Luna de Sus-Gilău and Baciu, with access to the primary road transport arteries such as DN1-E60, A3, and DN1F-E81.

At the end of the results chapter, it is worth mentioning that the methodologies discussed in this thesis have been successfully applied and validated in professional practice. To demonstrate this, two projects were selected and presented, focusing on two functional urban areas in Europe: Rzeszów, Poland and Brno, the Czech Republic. These areas are comparable to the region studied in this thesis in terms of territorial context, rank in European regional systems, and other aspects. It is also important to note that the author collaborated with World Bank urban development specialists to carry out these projects, and the results were used to inform the territorial development policies and strategies of the respective regions.

CHAPTER 5 - FINAL ASPECTS

In order to proactively manage the challenges caused by the unprecedented dynamics of territorial development in recent decades, geographic information systems and remote sensing technologies are increasingly used as tools for analysis, assessment and forecasting of territorial development. Experience shows that they are particularly useful and capable of informing decision-makers and spatial planning specialists and of providing the basis for optimal intervention solutions to prevent the negative effects of these phenomena.

As the title already emphasize, the main aim of this thesis was *to investigate and demonstrate how geographic information systems and geospatial data, in particular remotely sensed data, can be implemented and used in the analysis, evaluation and forecasting of territorial development.*

The research focused on several key aspects that capture the evolution, current status and possible future development directions of the studied area. The most important of these were: analysis and assessment of the dynamics of urban growth; determination and assessment of changes in land cover and land use; development of forecasting scenarios and analysis of land suitability to assess their development potential for different functions.

The results of the research demonstrate the effectiveness and usefulness of the methodologies used in this approach in the process of multi-temporal assessment of the dynamics of territorial development. GIS technology offers a wide range of tools, particularly powerful and capable in terms of analysis and forecasting of territorial processes, which allows geographers and specialists in different fields of activity to better model and understand the complexity of territorial development.

The application of spatially distributed models, such as ANN-CA and Markov in order to determine transition potential and to produce forecast scenarios of future spatial change can help to anticipate trends and inform policy decisions and urban planning regulations. These highly complex models can be used to simulate scenarios of future urbanization patterns and provide information on the potential impact of changes on the environment and society.

The implementation of multi-criteria assessment models for land suitability analysis provides a systematic, yet flexible approach that allows, on the one hand, the *determination of areas with high development potential for specific functions* and, on the other hand, *the identification of areas that are incompatible or restricted for certain types of development*.

In addition, it is important to note that the impact of this research transcends the boundaries of academia. The methodologies presented and used in this study have been successfully implemented in numerous World Bank projects, both nationally and internationally, demonstrating their practical applicability in the context of real-world challenges.

As already stated in the preamble, the *general objective* of the research was to *investigate, determine and apply the most appropriate methods and practices for implementing GIS and remote sensing technology in the process of developing analyses and forecasts that form the basis of territorial development strategies and decisions*.

To attain this objective, we proposed developing a working methodology with an inherent logic that ensures the progressive fulfillment of the subsidiary objectives of the primary theme while increasing the degree of complexity of the analyses and their relevance from the perspective of predictive requirements. This was, of course, preceded by a crucial theoretical foundation of an adequate conceptual framework. In other words, *we have aimed at structuring a certain optimal algorithm to follow (as a working hypothesis)* and next we intend to summarize both its main steps with the corresponding elements of content and the most relevant results, insisting mainly on those that give originality and scientific value to the present study.

Thus, an important first step has been taken towards *refining the methodology for the relatively fast and accurate delineation of built-up areas* based on Landsat satellite imagery.

The methodology proposed in this study gave excellent results, as demonstrated by the very good values obtained in the validation and evaluation processes of the delimitation accuracy. This involved the use of a wide range of qualitative and quantitative methods, which resulted in values above 85% in terms of overall model accuracy for each image analyzed and for each method used.

Also, in addition to relatively good values in terms of quantitative assessment in relation to the actual areas of built-up areas delimited, values of over 90% were obtained in the validation process of the results capturing the growth rate of built-up areas. This high level of accuracy attests that the results obtained on the basis of the methodology are reliable and can be further used for the analysis and evaluation of the dynamics of built-up areas from a multi-temporal perspective.

The results unequivocally show that with such a methodology, based on „out of the box" thinking and a „via negativa" approach, it is possible to *accurately delineate and map areas built by less traditional methods.* In other words, the exploitation of satellite imagery for the purpose of delineating areas specific to the built environment can also be achieved by eliminating all undesirable geographical features determined on the basis of spectral indices, such as those differentiating vegetation, water or bare ground.

Another important objective of the research, which was successfully achieved, was the *multi-temporal assessment of the spatial changes emerged in the process of territorial development of the CMA during the last two decades (2000-2020) and the setting up of forecasting scenarios for the 2025-2030 period*.

The methodologies used to determine and map the main land use and land cover classes for each reference point involved, on the one hand, the classification of satellite images and, on the other hand, the use of available geospatial databases.

Accuracy assessment has shown that a pixel-based approach is more suitable for medium resolution satellite images, while an object-based approach is more suitable for high resolution images. The study also found that RapidEye and PlanetScope high-resolution satellite imagery provided significantly higher accuracy compared to Landsat medium-resolution satellite imagery. However, in terms of temporal availability, this is much lower for high-resolution satellite images, which is a clear indication of the advantage of medium-resolution Landsat satellite images in the context of multi-temporal studies over a longer time period.

The datasets representing the main land use and land cover patterns obtained by image classification, as well as the results related to the built-up area delineation methodology, were analyzed by time series using change detection methods and techniques, as well as post-classification comparison, in order to qualitatively and especially quantitatively assess the multi-temporal dynamics of spatial development.

In the context that predicting future trends and the potential impact of urbanization is an essential aspect of the analysis of territorial development, it is also worth highlighting the fact that these datasets have been integrated into *spatially distributed models, such as ANN-CA and Markov, in order to produce forecasting scenarios.* These highly complex models can be used to simulate scenarios of future urbanization patterns and provide information on the potential impact of changes on the environment and society.

Extremely conclusive and, obviously, novel are *the quantitative results concerning the substantial transformations recorded at the level of the territorial unit which is the subject of this case study*. Cluj-Napoca metropolitan area has undergone major changes at an unprecedented pace in the last 20 years. Analysis and evaluation of the dynamics of territorial development has shown that the built-up areas of the CMA have doubled in the last 20 years, with a multi-annual growth rate of more than 115%. This indicates that there has been exacerbated urbanization over this period, and the analysis of socio-economic indicators shows a strong correlation of spatial development with a massive increase in the number of inhabitants, but also in economic productivity. Moreover, the analysis of the changes in land use and land cover shows that the massive expansion of built-up areas has taken place mainly at the expense of agricultural (especially arable) and natural land.

The most significant increase was noticed in rural communes situated along the main development axes (east-west and north-south), primarily in the functional urban area of Cluj-Napoca municipality, in the immediate vicinity of the urban core. However, much of this growth was unplanned and haphazard (known as urban sprawl), leading to various negative externalities over time, including chaotic development patterns, congestion, pollution, rising prices and cost of living, and increased demand for public services.

Forecast scenarios for 2025 and 2030 using ANN-CA and Markov models suggest that current trends are most likely to continue into the future, which could accentuate the current adverse effects and even generate a new set of negative implications for socio-economic and environmental conditions, undermining the basis for sustainable development. Moreover, in addition to the continuation of general trends, some areas within the CMA have a considerable potential for transition, driven by the availability of suitable land and increased demand in the housing market. These forecasts suggest that urgent action is needed to adopt policies and regulations that guide development in a sustainable and responsible way to minimize the negative impact of chaotic and unplanned urbanization. We believe that the results obtained on the spatiotemporal dynamics of the CMA will constitute a valuable archive and, by implication, an important benchmark for future approaches to this issue, which will remain inherently relevant in the future.

From the aspects outlined above, it is also clear that the analysis and forecasting of urbanization through the implementation of geographic information systems and remote sensing technologies is a crucial component of the analysis of territorial development. These methods and corresponding tools provide a broad and deep insight into urban growth patterns, the significance of territorial changes and the potential impact of these processes on the environment and society. The above-mentioned aspects justify us to consider that through this research we have succeeded in making meritorious scientific contributions in the field that are fully in line with other (more or less thematically related) approaches, and even bring significant added value if we refer to the *attempt to develop new practical tools for the analysis, forecasting, management and planning of spatial development.*

We also appreciate *that the present work contains substantial, original and relevant personal contributions to the advancement of knowledge in the field of spatial development* also by means of the *analyses of land suitability* it contains, which can inform the decision-making process in the context of spatial planning.

In addition, it is important to identify as precisely as possible areas which are incompatible or restricted for a particular type of development and also to identify areas which are suitable and well served in terms of technical infrastructure, thus making it possible to concentrate implementation efforts in those areas which are truly favorable. *Multi-criteria analysis of the suitability of land for different types of development* is thus a very useful tool both for rational and efficient development planning - providing support in the decision-making process - and for attracting and directing investment. The growing importance of these types of multi-criteria analysis and their usefulness in spatial planning and local development is all the more evident given the increasing pressure on the countryside and the often-chaotic nature of development processes.

The innovative character of the methodology developed for the feasibility analyses is demonstrated by at least the following features: *large volume of integrated data, level of granularity of data and analyses, unique combinations of variables, methodological flexibility and adaptability, scalability, complexity and inter-, multi-, and cross-disciplinary character.*

The importance and practical usefulness of such a model of analysis can also be demonstrated through the *implementation of the methodology used in the present approach in numerous projects carried out under the auspices of the World Bank at European level*.

In conclusion, the results obtained unequivocally demonstrate that geographic information systems and remote sensing technologies provide a broad range of highly capable and useful tools that offer valuable insights into territorial development. These tools can be applied from the past to the present and hold immense potential for future endeavors.

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