OBJECT-BASED IMAGE ANALYSIS OF REMOTE SENSING DATA

OBJEKTNO USMERJENA ANALIZA PODATKOV DALJINSKEGA ZAZNAVANJA

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ABSTRACT

Remote sensing has developed various methods and technologies for contactless and cost-effective mapping of large area land cover/land use maps and other thematic maps. The key factor for the availability and reliability of these maps for use in Earth sciences is the development of effective procedures for satellite data analysis and classification. The most appropriate approach for classifying low and medium resolution satellite images (pixel size is coarser than, or at best similar to, the size of geographical objects) is pixel-based classification in which an individual pixel is classified into the closest class based on its spectral similarity.

With increasing spatial resolution, pixel-based classification methods became less effective, since the relationship between the pixel size and the dimension of the observed objects on the Earth's surface has changed significantly. Therefore object-oriented classification has become increasingly popular over the past decade. This combines segmentation (which is a fundamental phase of the approach) and contextual classification. Segmentation divides the image into homogeneous pixel groups (segments), which are – during the semantic classification process - arranged into classes based on their spectral, geometric, textural and other features during. The intent of this paper is to present the theoretical argumentation and methodology of object-based image analysis of remote sensing data, provide an overview of the field and point out certain restrictions as regards the current operational solutions.

KEY WORDS

remote sensing, object-based image analysis, segmentation, object-based classification, semantic classification

IZVLEČEK

Na področju daljinskega zaznavanja se razvijajo različne metode in tehnologije za brezkontaktno in stroškovno učinkovito izdelavo kart pokrovnosti/rabe tal na velikih območjih ter drugih tematskih kart. Osrednjega pomena za zadostno razpoložljivost in zanesljivost takšnih kart za raziskave zemeljskega površja je razvoj učinkovitih postopkov analize in klasifikacije posnetkov. Za klasifikacijo satelitskih posnetkov nizke in srednje ločljivosti (njihova prostorska ločljivost je kvečjemu primerljiva z velikostjo geografskih objektov) zadostuje uporaba pikselsko usmerjene klasifikacije, pri kateri posamični piksel razvrstimo v najprimernejši razred na podlagi njegovih spektralnih lastnosti.

Ko povečujemo prostorsko ločljivost posnetkov, pikselska klasifikacija ni več učinkovita. Bistveno se namreč spremeni razmerje med velikostjo piksla na eni ter razsežnostjo in detajlom opazovanih elementov (objektov) geografske stvarnosti na drugi strani. V zadnjem desetletju se zato vse bolj uveljavlja objektno usmerjen pristop obdelave podob. Ta združuje segmentacijo, ki je temeljna faza za razmejevanje geografskih elementov, in klasifikacijo, ki je semantično (kontekstualno) podprta. Segmentacija razdeli podobo na homogene skupine pikslov (segmente), semantična klasifikacija pa jih nato razvršča v razrede na podlagi njihovih spektralnih, geometričnih, teksturnih in drugih lastnosti. Namen prispevka je predstaviti teoretično utemeljitev in metodologijo objektno usmerjene obdelave v daljinskem zaznavanju, podati pregled stanja na področju ter opozoriti na nekatere omejitve tehničnih rešitev.

KLJUČNE BESEDE

daljinsko zaznavanje, objektno usmerjena analiza podob, segmentacija, objektna klasifikacija, semantična klasifikacija

1 INTRODUCTION

Satellite systems provide various data on the Earth surface, its properties and are a source of obtaining up-to-date information as regards the current state of the surface. The information (product) that we wish to retrieve from the satellite image is a thematic map, most commonly a large area land cover/land use map, however change detection maps are becoming increasingly sought after. The key factor in the accuracy of satellite-data-based thematic information lies in the efficient procedures used to classify satellite images. The great importance of such procedures is revealed through numerous past studies and devoted research (Schowengerdt, 2007; Oštir, 2006).

The main goal of the classification is to detect and name the elements (geographical objects and phenomena) on the Earth surface (fig. 1). With the use of visual (manual) interpretation (fig. 1a) the operator tries to define land use classes by selecting the closed groups of similar pixels. Digital (automatic) classification defines classes by the means of spectral and/or geometric, texture, context, temporal information combined with mathematical (statistical) grouping into classes (Navulur, 2007; Oštir, 2006). Digital pixel-based classification (fig. 1b) uses the pixel's spectral signature to allocate each individual pixel to the most appropriate thematic class. On the other hand, digital object-based classification (fig. 1c) starts off by grouping pixels with common structural characteristics, and then these segments are allocated into the correct thematic classes based on several attributes. Thus, object-based classification combines the advantages of both, visual interpretation and pixel-based classification.

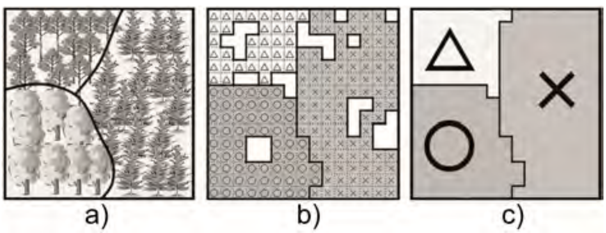

Figure 1: Different classification approaches, performed on a vegetation example (Blaschke et al., 2008): a) visual interpretation, b) pixel-based classification and c) object-based classification.

On the satellite image the surface reflectance is registered in the form of digital values which form a matrix of pixels. Therefore all original digital classifications were based on the pixel-based approach. This approach focuses on the individual pixel, which in general does not present the semantic unity of geographical reality (geographical object) and neglects the importance of the neighbouring pixels.

Alongside the development of satellite systems with a spatial resolution below 1 m, a substantial change in the ratio between the pixel size and the dimension of the observed object has occurred during the last decade, during which the size of the pixel became substantially smaller than the mean size of the observed object (fig. 2). Pixel-based methods are not effective on (very) high resolution images, since these include far too many details. Thus, experts started refocusing from individual pixels to their group representations, i.e. objects, as the most suitable input data for analysis. The object-based approach enabled the use of various disciplines within the process of detecting and distinguishing between different geographical objects. Thus data mining techniques, the analysis of vector attributes and above all, various remote sensing data (spectral, geometrical, contextual, morphologic and temporal) characteristics were utilised (Navulur, 2007). The main principle of object-based classification reads as follows (Blaschke et al., 2008): the complex and heterogeneous content of the Earth surface displayed on the satellite image must be described in the best possible way; all content has to be intuitively understandable to the users.

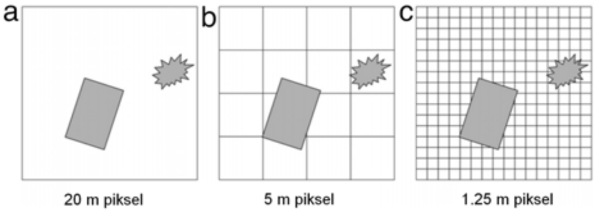

Figure 2: Ratio between the size of the geographical object and spatial resolution (Blaschke, 2010): a) small resolution: pixel size is significantly larger than the objects; b) medium resolution: pixel size is comparable to the objects' dimension; c) high resolution: pixel size is substantially smaller than the objects, pixels need to be grouped into segments and later objects.

The second chapter provides a historical overview of the transition from pixel-based analysis of satellite images to an object-based one, along with the reasons for this transition. The third chapter defines and explains the terminology within the object-based analysis. In the fourth chapter the methodology of object-based analysis is presented along with the description of the basic steps; the advantages and limitations are summarized. The fifth chapter outlines the typical applications of object-based classification. In the discussion we focused on the evaluation of this methodology, together with the possible development directions; at this we leaned upon the published and our own experiences.

2 BACKGROUND OF OBJECT-BASED ANALYSIS OF SATELLITE IMAGES

2.1 Pixel-based analysis of satellite images

Remote sensing enables us to obtain information about the Earth surface in the visible, infra-red, and micro-wave spectra. The sensors in the first satellite systems were multispectral, with which they compensated for their lower spatial resolution. Different land types reflect the sun energy in different ways, thus their spectral response varies, and this is what enables their analysis via the spectrometric processes. During the pioneering times (1970s) it seemed natural to treat the individual pixel with a desktop spectrometer, thus the pixel was used as the basic entity for analysis within remote sensing from the very beginnings (Schowengerdt, 2007; Liang, 2004). At the same time the first digital methods for grouping pixels into classes (classification) emerged, and this helped to compensate for the absent studies of spatial patterns. Therefore, pixel-based analysis became a common praxis in the remote sensing data studies. At the time it was stated that the interpretation of satellite data was predominantly in the domain of human capabilities (Oštir, 2006). Nowadays, pixel-based methods have been thoroughly studied and are mathematically precise (see: Schowengerdt, 2007; Oštir, 2006; Lillesand et al., 2004; Albertz; 2001; Richards and Jia, 1999). Pixel-base classification is based on the so called spectral signature, i.e. the characteristic reflection of electromagnetic waves from the Earth's surface which is wavelength dependant (Oštir, 2006). Most methods are based on cluster analysis, and the two most common approaches are: a) unsupervised classification in which the algorithm automatically finds the best pixel candidate (on the basis of a previously selected number of classes) and classifies them according to the statistically closest membership; b) supervised classification, which utilizes the training sample patterns and reference data for the statistically-based sorting into classes.

In the following decades (post 1970s) the research was primarily oriented towards methods of (pre)processing digital images (radiometric and geometric corrections, classification, change detection). The main focus was placed on the preparation of (semi)automatic procedures for processing and analysing satellite images, with the intent to promote remote sensing to a broader group of users (Oštir, 2006). The fact that an individual pixel did not represent an entity of geographical reality has been neglected for three decades. This was mainly a result of the intensive development of pixel-based algorithms, but also due to software and hardware limitations.

2.2 The transition from pixel-based to object-based analysis of satellite data

Pixel-based analysis is harder to perform on high resolution data. As this analysis was developed for medium resolution images (10 to 100 m), it was less effective and more time consuming when used on high resolution data. The need for better results from the studies of the changes in the Earth surface ultimately culminated in the necessity for a completely new approach (Blaschke in Strobl, 2001). A part of the ineffectiveness of the pixel based method was grounded in the fact that a high percentage of the interpretation of change detection images (categorization of the spatial samples of the identified changes) remained in the hands of the human interpreter, which means that the time consumption and content aspect should not be neglected. In their first publication Blaschke and Strobl (2001) emphasized the problem that statistical analysis focuses exclusively on individual pixels instead of focusing on the spatial patterns formed by the pixels. Even though this statement was not new (Hall et al., 1995; Cracknell, 1998), it became obvious that an increasing number of studies and applications started to move towards the segmentation of the image. The segmentation of the satellite image (at fist manual (vectorisation), later digital) was occasionally used in remote sensing applications already in the 1980s and 90s (Haralick and Shapiro, 1985; Pal and Pal, 1993).

The key motives behind the transition from pixel-based to object-based analysis of remote sensing data were: (1) the demand for improved interpretative values of remote sensing data in different applications (mostly in time comparison studies, and manifestations of remote sensing data used for planning); (2) increasing the availability of high resolution satellite data, on which one can observe surface objects in greater detail (including the increasing interest in the contextual validation of the image content); and (3) higher level of development of technological equipment and algorithms used for processing remote sensing data (accessibility to a wider user society; transfer of GIS object-based spatial analysis towards the field of raster remote sensing data and their particularities).

Thus it was only during the last decade that the key shift in the understanding of the basic entity of remote sensing data developed in synchronisation with the development of the more complex processing algorithms and the integration of remote sensing data into GIS. The object replaced the pixel as the basic entity.

2.3 Object-based analysis within remote sensing

At the end of the previous century object-based image analysis became common in the fields of computer vision, bio- and neuro-medicine.This was mainly a result of the increasingly efficient techniques used in the domain of pixel intensity values (Gonzales and Woods, 2002). At first the transfer of these algorithms into the field of remote sensing was not very successful; the newly developed methods did not yield effective results. There were three reasons for this. Firstly, satellite images usually cover a much larger area than the images for which computer vision algorithms were developed. Secondly, objects that are of prime interest usually fail to have a 'typical' form on satellite images, and in most cases they also lack clear and unambiguous edges. A given object (such as: a building, forest, water) may have a variety of presences in the sense of its position, size, shape and spectral domain. As a consequence the set of possible objects is heterogeneous and unmanageable. And thirdly, satellite images usually represent multispectral data, they are acquired at different dates (time periods) and they have different resolutions, all of which influences the methods and contents of processing the 'searched' objects (Schiewe et al., 2001). The listed characteristics dictated the development of algorithms that were tailored to suit satellite images (Castilla and Hay, 2008; Blaschke et al., 2008; Johansen et al., 2011).

While object-based analysis was known within geographic information systems and digital image processing, within remote sensing the object-based approach was limited to a few individual initiatives and tests that ranged from the early beginnings to the nineties (see Horowitz et al., 1975; Ketting and Landgrebe, 1976; Mason et al., 1988; Beaudoin et al., 1990; Quegan et al., 1992). These studies used manually segmented images, and only a few statistical attributes were calculated for each segment, most of which were related to the spectral characteristics of an individual spectral band (mean value, maximum, minimum, standard deviation). However, the first attempts were challenged by the radiometric characteristics of satellite images (segment radiometric variability) and by the weak software support. However in the nineties, when (due to the higher spatial resolution and consequently higher number of pixels within an individual segment) geometric, texture, conceptual and other attributes could also be assigned to each segment, the process of converting a satellite image into a thematic map finally moved towards the object-based analysis (Johansen et al., 2011).

With the appearance of the eCognition software in 2000 object-based analysis experienced a true boom. This software was the first commercial product that could be used to perform a quality object-based analysis of multi-spectral data. Some years later this was followed by software modules ERDAS Imagine (module Objective), ArcGIS (Feature Analyst) and ENVI (Feature Extraction within ENVI Zoom). Regardless of the extended software support the object-based analysis field remained complex, thus researchers established a biannual scientific conference at which they started an initiative with which they wished to introduce a new scientific field -

GEOBIA (Geo-Object-Based Image Analysis; Lang et al., 2006; Blaschke et al., 2008; Addink and Van Coillie, 2010). The central motto of this new sub-specialty of geographic information systems is that a homogeneous segment obtained from remote sensing data should be used as the basic research entity. The main goal is to support the development of computer (automatic) processes used for the detection of homogeneous segments in satellite data, along with their complete analysis including all theoretical and conceptual support (GEOBIA, 2011; Hay and Castilla, 2006).

Nowadays, object-based analysis of satellite data is well-established, and there is a common consensus that it is based on the concepts of segmentation, edge-detection, as well as object detection and classification, all of which have been present in the field of remote sensing already for decades (Johansen et al., 2011).

3 TERMINOLOGY

Space is an objective geographical certainty, a physical environment, our three dimensional physical reality, in which the basic study elements are represented by the various phenomena, their structure, condition, purpose, reciprocal connections and development tendencies. The idea of geographical reality is indisputable, however in their different databases various expert fields name and define the role and modelling of the basic elements of geographical reality – *geographical entities* differently (elements, structures, objects, and phenomena). In the studies of the Earth's surface geography and cartography use the terms *geographical entity* (sometimes element) and *topographic object* (table 1) as interchangeable terms (GTM, 2005). The two can be differentiated between as the adjective topographic is most commonly used in connection to larger details (or scales), while the term geographical is used for smaller ones; the term geographical is also linked to the description of reality, while topographic is linked to the contents of a (topographic) database or (topographic) map (Dušan Petrovič, personal communication). Within geographic information systems (GIS) the geographical entity is as a rule applied to the description of reality, while the geographical object is applied to the presentation of the entity within the database (Šumrada, 2005).

The terminology is thus often linked to a group of factors: the subject (and spatial dimension) of the studies, the instrument of observation and the way and manner in which the analysis is performed. The object oriented analysis discussed in this article merges from the observation of the geographical reality in the images and from their treatment with geographical informational systems. The images depict the Earth's surface (geographical reality) as a two dimensional matrix of pixels with accompanying spectral attributes. We wish to describe (map) the geographical entities observed on the images, thus they are the same or at least similar structures, objects and phenomena, as charted on thematic, or conditionally on topographic maps. The geographical object, an expression widely used in object oriented analysis (GEOBIA, 2011), does therefore not differ in its meaning from the term topographical object. Definitions of certain general terms as well as certain specific terms used within the object-based analysis of remote sensing data are provided in table 1.

Geographical entity	Geographical entities are the building blocks of our real (wide) world, (Šumrada, 2005) with their own identities and important characteristics. They are real objects and phenomena on the Earth's surface that cannot be further divided into the phenomena of the same type. They are entities of geographical reality. Topographic objects on the Earth's surface. Also: geographical object (GTS, 2005). Refers to the description of reality.
Geographical object	Representation of a geographical entity in the database (Šumrada, 2005). Within object-based analysis of satellite data it is a synonym for geographical entity.
Geographical object, topographical object	Object, part of the Earth's surface, part of another planet or of a natural satellite with a known identity. Also: topographic entity (GTS, 2005). It often refers to contents of a topographic database or map (Dušan Petrovič, pers. comm.).
Object-based analysis, object-oriented analysis	Series of processing steps, in which the content analysis of the image (satellite or aerial) is applied to the recognition (segmentation), determination (classification), evaluation (accuracy and post-classification assessment) and analysis (e.g. changes, comparisons, mapping) of semantically clear spatial entities (homogeneous areas, structures, objects, phenomena) and not on the analysis of individual pixels.
Segment	Represents the structural delineation of a geographical entity (phenomenon, object) in the database, in accordance to the characteristics presented on the image. It is homogeneous in content, closed, discreetly limited to the area on the image. It is vector data (polygon), which defines the area for computing the attributes.
Attributes, object attributes	Describe the characteristics of the segment and serve as a defining or classifying element for the corresponding object or object class. Attributes can be of the following types: spectral, geometrical, structural, textural, temporal and other.
Object	Is an individual sample of one or more segments, classified with regards to their common characteristics and relations. Every object belongs to a thematic or object class. It is a representation of a geographical entity within the database (Šumrada, 2005).
Object class, thematic class	Is a thematic group or category that incorporates objects of the same type (e.g. gravel road). It is result of image classification, therefore it often integrates elements of land use/land cover. Within cartography it corresponds to object type (Dušan Petrovič, pers. comm.). A number of object classes can be merged into object groups, which can in turn be merged into one or more object domains (depending on the aim of the task).
Object group	Merges related object classes/types (e.g. roads). It is a super-class of object types.
Object domain	Is the highest hierarchical level of the object catalogue (e.g. transport infrastructure, hydrography, relief, buildings).
Object catalogue	Is a register of all definitions and arrangements of object classes/types, their characteristics (attributes), and relations between objects and phenomena. Sub-classes and super-classes (object types) build a class hierarchy that is realized through the principle of inheritance between classes (Šumrada, 2005).
Object-based classification	Is a process of classifying images with respect to semantic information that is not present within an individual pixel. In this process we recognize objects as well as relations between them (Oštir, 2007). It is a way of organising image processing that enables sorting and merging segments into objects and/or object classes/types (based on their common characteristics and defined semantic model). Shorter: object classification, semantic classification, contextual classification.
Semantic modelling	Reflects conceptual (notional) modelling; (Šumrada, 2005) i.e. processes of recognition, interpretation and simplification of reality into a corresponding semantic model for particular use.

Table 1: Definitions of certain terms that are characteristic for object-based image analysis of remote sensing data.

Within the object-based analysis we are dealing with two understandings of objects: a) *objects on the image* (i.e. segments that are already classified into objects, classes) and b) *geographical objects* (geographical entities, topographic objects). Geographical objects are real objects and phenomena on the Earth's surface, they are entities that belong to the geographical reality. Objects on the image are limited regions on the image that were created with the segmentation and classification processes; they have given spatial, spectral and textural characteristics. They are unified in the selected characteristics, and distinct from their neighbourhood. Objects on the image (alone or in groups) are – in various stages – simplified representations of geographical (topographical) objects and natural phenomena. Individual objects (e g. gravel road 1, gravel road 2) belong to a given object class (gravel road), which belongs to an object group (roads) and further to an object domain (transport infrastructure). Sub-classes and super-classes of object classes represent a hierarchical arrangement of classes and their characteristics (attributes, relations) within the object catalogue. When a particular satellite image is processed (classified), the content of the corresponding object catalogue depends on the particular task in hand, however it makes sense to respect the general scheme and common object naming, as used in cartography (thematic and topographic).

4 METHODOLOGY OF OBJECT-BASED IMAGE ANALYSIS

Within object-based analysis of remote sensing data homogeneous regions (segments) obtained from satellite images are used as basic entities. Object-based analysis consists of various procedures for obtaining segments and their characteristics (attributes), for analysing these segments, sorting them into classes or objects (classification), verifying them and for error removal (post-classification).

4.1 Processing steps in object-based classification

Object-based classification consists of the following processing steps (fig. 3):

- segmentation and computation of spectral, geometric, textural, conceptual and temporal attributes,
- object (semantic) classification,
- post-classification (verification, error elimination) and result validation.

The basic input data is represented by multispectral satellite (or aerial) images. However, depending on the aim of the particular object-based analysis, other auxiliary data layers can be added, and this helps to fine-tune the process of sorting segments into object classes. An additional or auxiliary data layer may be represented by a thematic mask used to include/exclude particular areas, and/or a data layer describing geomorphologic (slope, height) or other surface properties.

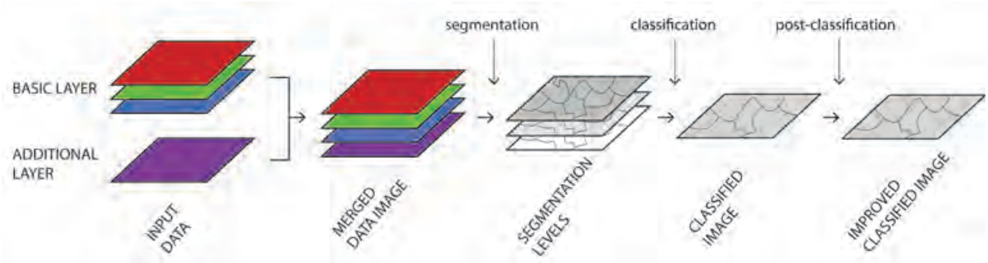

Figure 3: Processing steps in the object-based analysis of remote sensing data.

Segments produced within the first step of object-based classification influence the final classification results (Blaschke et al., 2008). There is a causal relationship between segmentation and classification, as the particularities and errors of the first transfer onto the latter. Thus the characteristics and quality of the attributes that are later used to evaluate and sort objects are directly dependant on the way the segments are produced. This nature of the object-based approach can be illustrated by a spiral, in which every step is based on the previous steps (fig. 4).

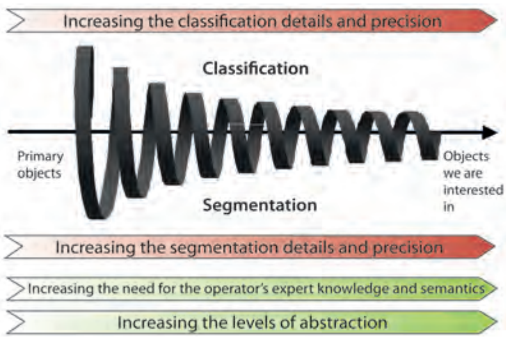

Figure 4: Common nature of the object-based classification process (Blaschke et al., 2008).

4.1.1 Segmentation

The greatest challenge within object-based analysis is to perform satisfactory segmentation – achieve just the right number of spatial entities (objects) that differ in size and other characteristics - with a single procedure (Blaschke et al., 2008; Nussbaum and Menz, 2008). In the segmentation process we use several homogeneity measures (ENVI, 2004) to divide an image into homogeneous segments by grouping the neighbouring pixels with similar attribute values (intensity, texture, colour, etc). Generally speaking segments prepared in this way do not represent the real object on the image, but rather their component parts. If optimal segmentation parameters are selected, it is expected that the image will be divided into semantically important segments, which can be recognized and classified in the steps to come.

Segmentation is used in different sciences (medicine, neuro-informatics, telecommunications), therefore there are several segmentation algorithms available. However, most of these algorithms fail to consider multispectral or spatial information, therefore they are generally unsuitable for classifying remote sensing data. Thus, most cases are covered by two types of algorithms (Gao et al., 2007; Nussbaum and Menz, 2008), i.e. the edge-based, the region growing, or a combination of the two (Schiewe, 2002). Which technique is better and more efficient, depends on the data (character of the observed area), the selection of the parameters and the aim of the analysis. The so called multi-scale approach, in which the object characteristics are studied for several different scales and a multi-level connectivity is established and has proven to be advantageous (see Baatz and Schäpe, 2000; Definiens, 2011). Segmentation algorithms group individual pixels into segments according to the following criteria: homogeneity within the segment, the ability to be separated from the neighbouring elements (dissimilar), and shape homogeneity. Since the three criteria sometimes contradict each other and can therefore not be fulfilled at the same time, the segmentation algorithms stress one or two of them (Nussbaum and Menz, 2008).

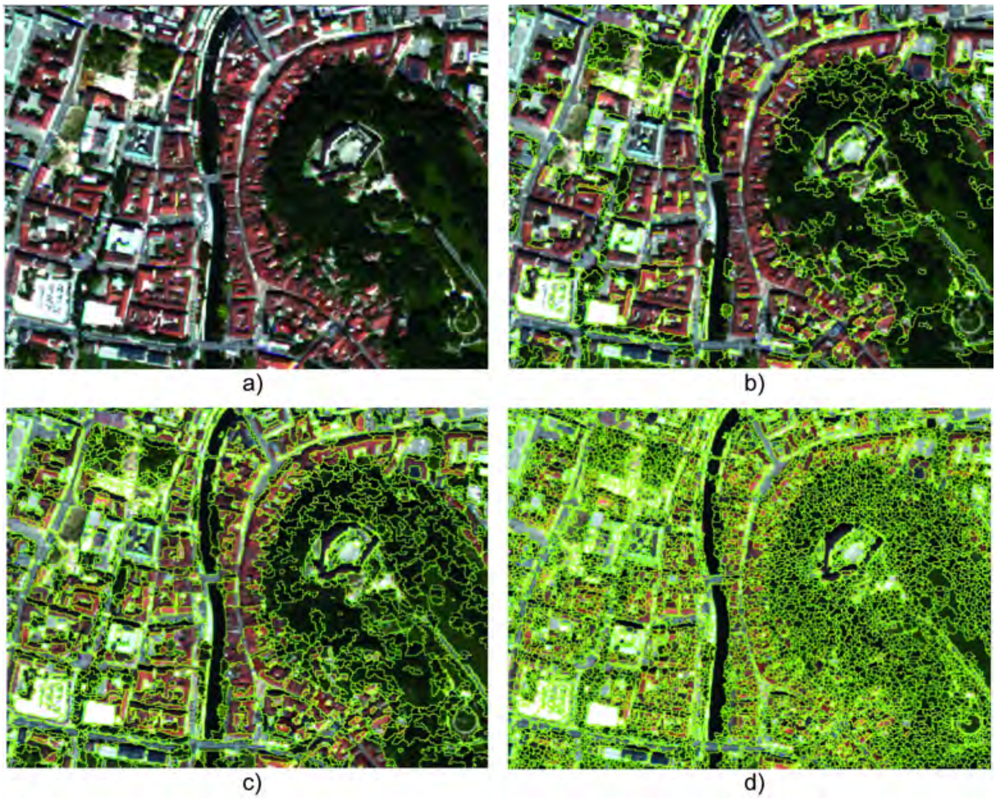

Figure 5: a) A detail of the satellite image of the centre of the Slovene capital of Ljubljana is shown segmented with different segmentation parameters. Examples of under- (b), correct (c), and over-segmentation (d) are shown.

The segmentation process faces two common problems: one is over-segmentation, in which the tonality contrast between the neighbouring segments is too heavy, and the other is under-segmentation, in which the tonality contrast is insufficient, thus the segments are not dissimilar. Fig. 5 shows examples of over-, correct, and under-segmentation. Over-segmentation is less problematic than under-segmentation, since it is easier to merge the segments than split them during the steps that follow. Nevertheless, segmentation is considered to be appropriate when no extreme prevails (Blaschke et al., 2008).

Segment attributes describe the characteristics of individual segments. They are (Navulur, 2007): geometric (e.g. area, perimeter, oblongness, compactness), spectral (e.g. mean value, standard deviation, minimal and maximal value of each band), textural (e.g. span, entropy, variability), attributes of the spectrum band proportions (e.g. vegetation index), contextual (e.g. proximity of the neighbouring pixels, distance), temporal (e.g. time span, date, stability) and other attributes. The number of calculated attributes can be large, for it can run up to a few dozen.

4.1.2 Object (semantic) classification

The object (semantic) classification uses the segment characteristics to sort them into object classes. Individual segment characteristics (attributes) are compared, and membership in a particular class is established (Nussbaum and Menz, 2008). Various approaches are used to define segment membership with regard to objects or object classes. The two most common are: defining training samples, and defining rules on the basis of representative threshold values (usually decision trees) that are usually defined for each target object class separately. The classification (execution of rules) is usually performed by a selected method or with the use of a classifier. Some of the more established classifiers are (Schowengerdt, 2007; Oštir, 2006; Lillesand et al., 2004):

- parametric and non-parametric statistical classifiers (e.g. K-Means, ISODATA, minimum distance method, maximal probability method, nearest neighbour, parallel-piped method, vector machine support (SVM variations)),
- classifiers based on neural networks (with loop information, Kohonen method),
- classifiers based on machine learning (decision trees, classification and regression trees),
- classifiers based on fuzzy logic (membership) etc.

Fig. 6 compares the results from two semantic classification systems (training samples, decision trees) on the Landsat image depicting the Ljubljana surroundings. The results are rather different; based on the visual evaluation of the correctly and incorrectly classified objects we estimate that the method with training samples yielded a better result.

Defining the set of rules can be extremely demanding when classifying heterogeneous geographic reality (i.e. when we are simultaneously analysing several objects and object types). Namely, the rules can sometimes overlap or be in opposition to each other, which of course reduces the accuracy of the classification results. Classifications based on the decision tree are known to yield good results when analysing surface phenomena (mostly anthropological) that was built in compliance with certain standards and can therefore be relatively easily described by a set of rules (Lang and Blaschke, 2003). The same holds true when we analyse clearly distinguishable patterns on an image, e.g. water on a radar satellite image (Veljanovski et al. 2011a).

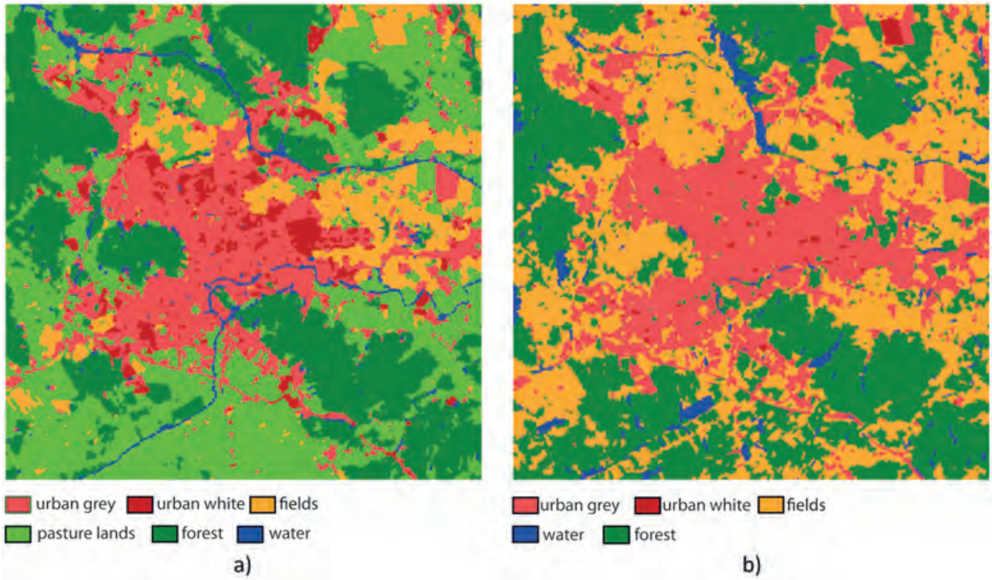

Figure 6: Classification of the Landsat image depicting the Ljubljana surroundings: (a) training samples (SVM was used as a classifier), (b) rule-based (decision trees).

The quality of the final classification definitions is linked directly to the quality of the segmentation and the quality of the classifier. However, we encounter significant questions with no uniform answers, to name a few: Are segmentation and classification processes reliable, consistent and repeatable? Do the results depend on the chosen model? We were unable to find any systematic comparative studies dealing with these questions in the available sources.

4.1.3 Post-classification

Post-classification serves to eliminate the evident errors (wrong classifications) and generalize the results. Evident errors can be eliminated by visual control, field inspection and/or comparison with the reference source (if available). All of these procedures are predominantly manual, thus they are time consuming.

In order to improve their visual quality and the content of the final result (the thematic map) the obtained object classes need to be generalised. If, for example, we do not wish to keep the small objects, we can eliminate them by merging them with the dominant neighbouring classes using the 'clump and sieve' procedures (Kokalj, 2006). Both procedures work only on raster images. Amongst the post-procedures for finalizing vector thematic maps we need to mention line-smoothing. As it overcomes the problem of broken lines (which are a result of the pixel shape and their distribution) this procedure is especially useful when object classification is performed on medium resolution satellite data.

4.1.4 Assessment of classification accuracy

Similar methods to those used for pixel-based classification are also used to validate the results of object classification: the quality of the distribution of segments into object classes is assessed. A reference image or other spatial data with corresponding characteristics (time, content, area of interest) is used for comparison. The accuracy of the classification indicates the level to which the classified thematic data corresponds to reality (Campbell, 1996), therefore the difference between the thematic data and reality represents classification errors. The *confusion matrix*, given in the form of a crosswise table, uses percentages of correctly classified segments to present the relation between reference data and classification results (Congalton and Green, 1999). The classification is usually validated on the basis of sample ground points with a known location and thematic content, regardless of the data scale. For a valid accuracy assessment the compared data has to be harmonized from all aspects (spatial, temporal). The difference in the scale of the various data sources can lower the assessment quality, since this means that the level of generalization varies from source to source.

Such quantitative assessments are used to *assess the probability of correct classification* and the *general quality or reliability of the classification results*. Since all processing steps that lead to the final result also influence the final quality, more and more attention is given to the assessment of the quality of segmentation and semantic classification.

The overview of the techniques used to *assess the image segmentation quality* was given by Neubert et al. (2008). They also prepared an extensive study dealing with the efficiency of the measures used in accuracy assessment, which are currently implemented in various software modules for object-based image analysis. They stated that obtaining a relevant assessment of segmentation accuracy is a rather difficult task; this is mainly due to the variety of algorithms and the nature of segmentation, which is based on the parameterization of several decision factors.

Radoux and Defourny (2008) studied the assessment of segmentation output quality based on quantitative indices (*goodness* and *discrepancy indices*). They used goodness indices (normalized post-segmentation standard deviation, etc.) to assess the thematic accuracy of the segments, and discrepancy indices (the principle of the inter-class Bhattachary distance, which is a measure for both, standard deviation and mean value) to assess the accuracy of the segment boundaries. They discovered that goodness indices were good for detecting the differences between segmentation results that were processed with different parameter sets, and therefore they enable a systematic assessment. Since these indices fail to take into account the positional errors along the segment boundaries and do not recognize under-segmentation, the authors suggest that the two indices should be used complementary. With this we can not only asses, but also improve the segmentation, especially in the case of under-segmentation.

Schiewe and Gähler (2008) studied the *assessment of thematic uncertainty after classification*. They developed a new measure, which took into account the uncertainty of the reference data and combined it with the fact that most objects found in nature do not have sharp boundaries. This is based on the fuzzy certainty measure. This new measure models and assesses the inconsistencies between the object boundaries of reference data and the edges of the classification results.

4.2 Advantages and limitations of object-based classification

New methodology is developed either because it aims to improve the existing one(s), or due to a major shift in the paradigm of understanding the problem which results in the need for a new methodological approach. Within remote sensing a shift from the pixel-based analysis of high resolution data towards the object-based one clearly belongs to the latter.

The methodology for object-based classification has been established, however it is far from perfect. We have to keep in mind that the object-based approach is usually tailored to solve a specific problem, and this holds true for each and every processing step. From the given aspects we evaluate the abilities of object-based analysis and the current technical capabilities for implementation (Hay et al., 2003; Lang et al., 2006; Navulur, 2007; Blaschke et al., 2008; Nussbaum and Menz, 2008; Kanjir, 2009).

Advantages of object-based classification:

- It uses a vast variety of remote sensing data characteristics (spectral, spatial, temporal) and combines them with GIS functionalities in the various processing phases. Within the classification process: employment and consideration of additional information and data layers, additional relations such as distance, etc. expressed through various spatial functions. Within the post-classification process: smoothing and generalization.
- Object-based classification uses all available and usable segment characteristics for their classification (e.g. shape, texture, relations with other segments).
- Results (identified objects) are vectors, which demand easier post-processing than pixel-based classification results. To a certain degree the generalization can also be performed during the main processing phases (e.g. elimination of small objects based on their shape or size).
- It classifies the image contents into objects in a way that is close to the human understanding of the environment. The results are already generalized, since the classification uses clear semantic rules that can also be used to enhance or omit certain typical object characteristics (e.g. linearity, length, width, rectangularity of buildings) or enhance their key differences (e.g. typical size in nature).
- The fact that the basic computation entities are objects (and not pixels) reduces the demand on computer algorithms and at the same time enables the users to utilize more complex computation techniques and a wider set of data characteristics (introduction of conceptual attributes).
- Various free software for object-based analysess are on the increase, as is their compatibility and file format support.
- It is an interactive multi-phase process. It enables the intermediate results to be checked, and immediate improvements can be made through immediate parameter fine-tuning.

Limitations of object-based classification:

- When processing extensive databases (large area of interest, high spatial resolution, or both) powerful processing hardware is needed, since numerous pixels are processed simultaneously during the multispectral image segmentation.

- Segmentation has no uniform solution. Even a minimal change in the radiometric resolution, the segmentation parameters, or the pre-processing procedures yields different results.
- Object-based classification is a relatively new method of remote sensing, therefore there is no general consensus (nor enough studies) that would deal with the relation between the object obtained within the segmentation process and the geographical object. Similarly, the procedures for assessing the quality of different processing steps are neither numerous nor developed to the level that would be sufficient for their incorporation into commercial software.
- The levels and hierarchical relations between objects that are obtained at different spatial scales are relatively poorly studied. The processes that enable multi-scale object-based analysis do not have enough support in topological linking, querying through scale and object tracing with practical implementations.
- Due to the complex geographical reality and the diversity of satellite images upon which this reality is revealed, the processes were not designed to be fully automatic, but rather to suit a broad spectrum of different applications. Automatism thus remains limited merely to highly specialized tasks and to particular objects.
- From the point of view of discrimination/preservation of the basic geometrical object properties object determination is not strong enough. The repeatability of the discrimination process in various natural and technological conditions is poor.

The object-based approach is meaningful if it ensures advantages compared to other methods. Several studies compared pixel- and object-based classification. They showed that satellite data of medium (e.g. Landsat TM/ETM+ and SPOT-5) and high resolution (Ikonos, QuickBird, WorldView) yields better results with the object-based approach (Baatz and Schäpe, 2000; Willhauck et al., 2000; Hay et al., 2005; Kamagata et al., 2005; Manakos et al., 2000; Whiteside and Ahmad, 2005; Yan et al. 2006). Moreover, numerous practical applications show that certain phenomena (presence of selected geographical objects) can be faster and more reliably detected with an object-based approach (rather than a pixel-based one). On the other hand, studies showed that object-based classification did not outperform pixel-based classification on low resolution satellite data (100 to 250 m).

5 OUTLINE OF APPLICATIONS USED FOR OBJECT-BASED ANALYSES IN REMOTE SENSING

Numerous applications for an object-based approach of satellite data are presented in various publications and on the web. An important overview of the various studies is available on the web portal Definiens (2011) and on the portal ran by the Centre for Geomatics at the Salzburg University Z_GIS (2011). According to Blaschke (2010) the number of articles dealing with the object-based approach started to grow in 2000 and remains on the increase until today. At this point we will outline the main directions of the key object-based approach applications: analysing and monitoring larger areas of the Earth's surface (Blaschke, 2005; Chandra et al., 2005; Crase and Hempel, 2005; Laliberte et al., 2005; Whiteside, 2005), monitoring urban areas and their growth (Chunyang et al, 2005; Grenzdoerfer, 2005; Moeller, 2005), retrieving post-disaster data (Bitelli et al., 2004; Heremans et al., 2005; Kouchi and Yamazaki, 2005), monitoring nuclear objects (Niemeyer and Canty, 2001; Nussbaum and Menz, 2008), identifying vegetation (Peña-Barragán et al., 2011), monitoring habitats and biotopes, a precise analysis and recognition of vegetation types and agricultural areas. The enthusiastic reader is invited to find more details in the thorough overview by Blaschke (2010).

Most of the applications were implemented on eCognition software, while others used ENVI Feature Extraction and individual software solutions. The main challenges of the existing software solutions are correlated with the difficulties imposed by under- and over-segmentation, and with the absence of tools for assessing the quality of individual processing steps. Algorithms for improved segmentation and advanced object-based analysis are being intensively developed (Blaschke et al., 2008; Nussbaum and Menz, 2008; Navulur, 2007), and they will enable new implementations and applications.

5.1 Application of object-based analyses of satellite data in Slovenia

In Slovenia the first applications of the object-based approach were dedicated to the production and analysis of thematic maps (classification) for land use/land cover (Šabić et al., 2000; Kokalj and Oštir, 2006; 2007).

The object-based analysis of satellite and aerial images was applied more extensively for the needs of forestry and forest management (Kobler et al., 2006). Object-based analyses were successfully implemented for determining land use/land cover in the sub-alpine and agricultural areas (Kanjir et al., 2010), studying the growth of urban areas around Ljubljana (fig. 7; Kanjir et al., 2011a) and determining the flooded areas in the September 2010 floods from radar and optical satellite images as well as aerial images (Veljanovski et al., 2011a, 2011b). Grigillo and Kosmatin Fras (2011) used the object-based approach to detect buildings on satellite images. Some elements of the object-based approach were also used for detecting buildings for the needs of maintaining topographic databases (Grigillo et al., 2011). The multi-level object-based approach was used to determine the impermeable surfaces (soil sealing) within urban areas (Kanjir et al., 2011b). Advanced object-based analyses were also applied for mapping the different tree-types within urban areas and for detecting invasive plants in the Ljubljana suburbs (Đurić, in press).

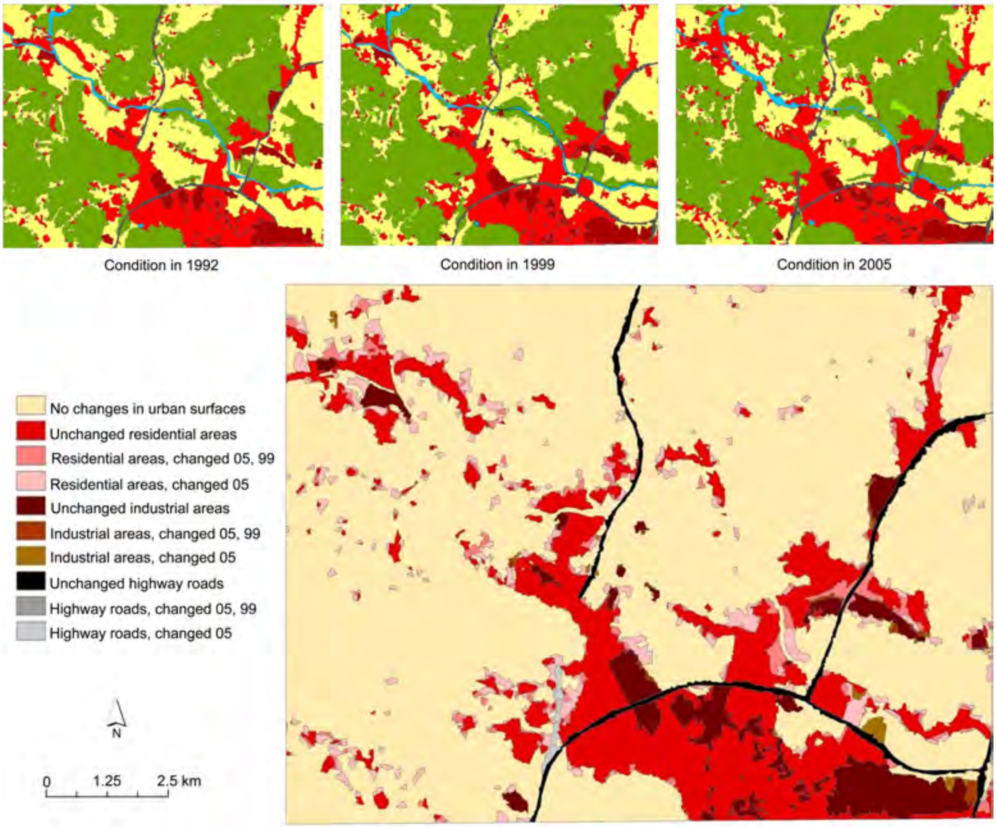

Figure 7: Object-based change detection of urban areas in NW Ljubljana and its surroundings. Above: results of the object-based classification from Landsat images from 1992, 1999 and 2005; based on training samples. Urban areas are displayed in shades of redcolour. Below: the change detection map of urban areas in between the given years. Brighter shades show growth (bright red for residential areas, bright brown for industrial ones).

6 DISCUSSION

Usually object-based approaches are adjusted to solve particular problems (e.g. recognition and monitoring of forest systems, detection of changes in urban areas), therefore their implementation is adjusted to specific needs. In order to produce effective and useful results it is important to understand all of the processing steps within the object-based approach.

The key processing step is the segmentation of the satellite image. This is far from trivial, for it implies three unsolved challenges. In the time-series studies we face a problem when we try to achieve consistency and repeatability of the processed segmentations with the same set of parameters on images that were acquired on different (consecutive) dates. In the comparison of data with different spatial resolution, the hardest task is to preserve the comparability of object recognition (different scales of observation, limitations of the measurement accuracy). However, the most common problem is how to tackle spectral and spatial variability of objects belonging to the same – or different – object type, and the variety of levels in detail, which we want to preserve for certain objects (e.g. outlines of buildings) but not for others (e.g. too fine details in large forest areas). The possible solution could be found in the multi-scale and multi-level object-based analysis, i.e. an analysis of satellite image contents at different scales. The results are promising, and currently the most practical difficulties are caused by the hierarchical connectivity of the components and the transfer of intermediate results from the thus created hierarchic system (segments and their properties in different scales) into the following processing steps (Hay et al., 2003).

Currently, the software support for object-based analysis is adequate in addressing individual, specific problems, e.g. single surface classifications. On the other hand multiple object analyses are poorly supported. Only when the multi-scale approach within the object-based analysis of satellite images will be significantly improved will this type of analysis lead towards a more coherent understanding of geographical objects – real ones as well as their representations on remote sensing images, independently of the input data source or of the used software.

6.1 Limitations of object-based analyses

The current limitations of object-based analysis of remote sensing data can be divided into those related to the theoretical background, or those that relate to its application in practice.

So far there is no consensus as to whether the goals of the object-based approach are achieved in the *perception of the structures within their environment (i.e. geographical objects)*, their representations on remote sensing data or in the results obtained through object-based classification. Studies dealing with the relation between the object created within the process of segmentation and classification and the real geographical object (assessing whether a particular created object corresponds to the one found in nature as regards its shape and form) are rare. Therefore we are not fully aware of the weak points in which most of the errors appear when defining the primary segments on the image, nor are we aware of the way these errors are transferred into semantic modelling (Hay and Castilla, 2006). In the near future we can expect that the development will move in the direction of a multi-level object representation and a multi-scale support for object recognition and monitoring. These will be followed by the development of new criteria for the assessment of the quality and adequacy of object-based analyses.

Geographical reality is a heterogeneous and complex (as regards relations) structure. The object-based analysis of remote sensing data offers a broad variety of attributes for semantic modelling. When solving a particular problem the user searches for a vast array of task-oriented data that he then combines. In general the system for best object recognition needs to be established for every particular task individually. In this respect a bank of *optimal attribute combinations* would be more than beneficial, at least for *representative objects*. We did not find any systematic studies regarding this topic.

The object-based approach includes several processing steps; all of which are more or less *parametric* (i.e. are processed on the basis of selected parameters). This enables us to adjust a set of classification rules to a particular situation, i.e. to the image characteristics and to the goals of our analysis. On the other hand, we have to be aware that such flexible parameterisation does not allow for a (perfect) transferability and repeatability of the process to other tasks or other data; this is possible only to a very limited extent (e.g. we can keep the set of rules but have to change the threshold values). Moreover, the transferability of the decision tree is always delicate, since this tree depends on every single characteristic of the image that it was built for.

The limitations of the current state-of-the-art object-based technologies are by far the most visible in the *time-series studies and change detection*, where we try to determine an optimal set of parameters that would enable process repeatability and result comparability for satellite images acquired on different (sequential) dates. Currently most problems are caused by the inconsistency of the recognition of the same object on different images. The segmentation of otherwise similar images (e.g. same satellite sensor, same resolution) yields no uniform solution. Once more it is better to use segmentation that recognizes functionality or typical representations of objects in several scales, or to use basic object geometries from different sources and reference data. On the other hand object-based time-series studies effectively surpass some acute limitations of the pixel-based approach (Veljanovski, 2008): they provide meaning to the change pattern; they ease the interpretation of the change pattern; the efficiency is not connected to the radiometric consistency of the time-series data; etc. As regards the technique and content object tracing is a demanding task within object-based change detection, for it needs to take into account the inconsistency (changeability) of the object's shape (boundaries) when recognized on different sequential images, as well as its real manifestation in time. Object tracing and the technological solution for analysing their real existences through time are at the moment unsolved issues, which are also practically unsupported in the current software.

Considering the capabilities of the existing software on one hand, and the potential of the object-based paradigm for analysis on the other, we can state that the possibilities for analysing the object spectral space (domain) remain almost totally unexploited. Therefore we can expect a shift towards the expansion of the set of computed attributes in the following directions: spectral signature of the object, description of the geometrical (sub)structure of the object, and similar. The introduction and proper use of these more complex attributes will substantially improve the possibilities of recognising and distinguishing objects with similar characteristics (e.g. ploughed fields – paved surfaces).

7 CONCLUSION

The continuous progress in the field of optical, radar and laser systems used for data acquisition produces increasingly detailed data sources (resolution increases). On one hand this improves the interpretation possibilities; on the other hand it makes the processing more difficult. Processing high resolution satellite images consists of processing steps that are similar to visual interpretation; they are not based on the individual pixel, but on groups of pixels – objects – and the relations between them. Object-based analysis of satellite data provides an interpretation that is an improvement on the pixel-based analysis and is also closer to the human understanding of nature. Thus, it enables a more coherent understanding of geographical objects in nature and their representations on remote sensing data.

Even though the use of object-based analysis of satellite data appeared and started to make a mark merely a decade ago, it is based on processing steps (segmentation, edge detection, classification) that have been in use within remote sensing for decades. Great progress was induced by the development of software, since this advanced in a relatively short time from a niche scientific environment into qualitative stand-alone products (eCognition remaining a synonym for object-based analysis) and increasingly capable software products used for satellite data processing (mostly as additional modules; e.g. ERDAS Objective, ENVI Feature Extraction).

Within the field of object-based analysis of remote sensing data we face extremely proactive research and development. Although several challenges have not been yet solved adequately, e.g. segmentation, change detection, result assessment, we can notice that applications are being developed in various fields. Object-based analysis of remote sensing data became a key factor in the multi-level analysis of the surface and as such presents an important link between remote sensing and geographic information systems. Namely, it reduces the gap between GIS information, the parameters obtained from different satellite sensors, and expert knowledge. Thus it enables tremendous opportunities for an (automatic) analysis of objects.

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