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Research paper

Mapping urban form and function at city block level using spatial metrics

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ABSTRACT

This paper focuses on the potential of urban metrics describing the presence and the configuration of built-up and open space areas for mapping distinct types of urban form and function at city block level. Next to traditional, patch-based metrics used in landscape ecology, alternative metrics are proposed, measuring the presence and the spatial arrangement of built-up and open space areas along a set of radial transects, along contours parallel to the urban block boundary and along the block's perimeter, as well as metrics describing the internal composition of the built-up area. Use of the proposed metrics for identifying different types of urban form and function was tested on the Brussels Capital Region. Large-scale vector data was used to define built-up structures and to analyse the morphological properties of the built-up area at block level. Decision tree classification was applied in conjunction with bootstrap aggregation to gain insight in the distinctive character of the defined metrics, and the robustness of land use and urban form classification based on these metrics. Our study points out the shortcomings of traditional landscape ecological metrics for mapping urban form and emphasizes the need for alternative approaches for analysing urban landscapes, more explicitly describing the morphological characteristics of the urban fabric.

1. Introduction

The increasing availability of spatial data and the proliferation of GIS-based processing and modelling tools holds great potential for monitoring urban areas and for characterising changes that occur within the urban fabric. Developing new approaches for analysing urban form and function, and for monitoring and modelling of urban dynamics has thus become an important topic in urban research, as well as in geo-information science and remote sensing. Urban growth models are increasingly used to predict future urban development using scenario driven approaches (Canters, Vanderhaegen, Khan, Engelen, & Uljee, 2014; Hosseinali, Alesheikh, & Nourian, 2013; Petrov, Lavalle, & Kasanko, 2009; Van de Voorde et al., 2016; Vaz, Nijkamp, Painho, & Caetano, 2012). Such models strongly rely on time series of land-use maps providing information on urban form and function, for model calibration and validation (Herold et al., 2005). Because land-use mapping is a tedious and time consuming process, data on urban land use is in most cases only available for relatively sparse time intervals, typically ten years (Barredo et al., 2003), making calibration of dynamic land-use change models difficult (Straatman, White, & Engelen, 2004; Van de Voorde et al., 2012). Mapping land use from land-cover data (e.g. aerial photographs, high-resolution satellite imagery, large-scale building maps, …) is also a rather subjective process, often leading to inconsistencies in documenting urban growth. This complicates the use of these maps in studies on urban dynamics, as well as in urban modelling work. Quantitative approaches for describing urban morphology, and for inferring urban form and function from land-cover data may help in developing timely, as well as spatially and temporally more consistent data sets for monitoring and modelling of urban areas, both for intra-urban analysis, as well as for inter-urban studies.

Typically, urban areas consist of different types of constructed and open spaces, i.e. roads, buildings, parking lots, green areas like parks and gardens, bare soil fields (construction sites, dump sites, etc.) and water bodies (ponds, lakes, rivers, canals, swimming pools, etc.). It is the presence, the size, the shape and the spatial arrangement of these urban land covers that define the morphology of urban areas. Spatial analysis of urban land cover may also reveal information about the function of urban spaces. The relationship between urban form and function formed the basis for various (semi-) automatic approaches for mapping urban land use from land-cover data (Barnsley and Barr, 1997; Herold, Goldstein, & Clarke, 2003; Van de Voorde, Jacquet, & Canters, 2011). Many of these methods rely on analysing the spatial arrangement of contiguous areas of the same land cover, referred to as patches. These patch-based approaches often make use of spatial metrics taken from landscape ecology, a research field where the use of metrics describing the spatial characteristics of the different components constituting the landscape is common (Turner and Gardner, 1990;

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McGarigal, Cushman, Neel, & Ene, 2002).

Herold, Scepan, & Clarke (2002) were among the first to suggest the use of spatial metrics, as proposed in landscape ecological research, to describe the composition and the spatial arrangement of the different elements that constitute the urban fabric. Since then the potential of spatial metrics for analysing urban form and urban dynamics (Herold, Goldstein, & Clarke, 2003; Herold, Couclelis, & Clarke, 2005; Lv, Dai, & Sun, 2012; Liu et al., 2010) and for linking urban form to urban function (Herold, Liu, & Clarke, 2003; Novack, Kux, Feitosa, & Costa, 2010) has repeatedly been demonstrated.

Despite the promising results obtained with landscape metrics in the analysis of urban form, spatial metrics originating from landscape ecology were not specifically developed for capturing characteristic properties of urban morphology. Herold, Couclelis, & Clarke (2005) argue that the strong difference in structure between urban and natural landscapes calls for the development of dedicated urban metrics able to capture the typical structural features defining urban areas. It is therefore interesting to explore the potential of new ways of characterising the morphology of urban areas, and to study the relationship between urban form and function using metrics, specifically developed for the urban environment. Yoshida and Omae (2005) analysed the morphological properties of urban areas by means of urban metrics characterising the two- and three-dimensional structure of the built-up area, the latter being described by measures such as the total area covered by vertical walls and the average volume of each built-up cell within an urban block. Although in their study a clear relation between metric values and urban land use at block level is shown, due to the strong variance of metric values within single land-use classes, no attempt was undertaken to assign blocks to different urban form/land-use classes based on their metric values. Louw and Sithole (2011) propose the use of building characteristics (size, compactness and distance to nearest neighbour), road features (width) and the road-building distance to differentiate residential from industrial or commercial land use. Hermosilla et al. (2014) demonstrate the potential of linking street based metrics, describing the streets' geometry, the presence of vegetation in streets and the relationship of street area to its adjacent built-up area and volume, complementing traditional two- and three-dimensional urban block metrics, to define distinct urban typologies.

This paper attempts to quantify relevant characteristics of urban form and function at the level of urban blocks, by describing the two-dimensional pattern of built-up and open space areas. Next to traditional landscape ecological metrics, the use of metrics describing the occurrence and alternation of built-up and open space area along radial transects and along contours parallel to the urban block boundary is proposed, to include more spatially explicit information on the positioning of built up and open spaces within and along the perimeter of an urban block. Additionally, metrics describing characteristics of individual buildings and their spatial configuration are incorporated in the analysis. Insight on the urban metrics' potential and its added value for distinguishing different types of urban form and function is assessed by applying a decision-tree based classification approach, using different ensembles of urban metrics. The discussion part of the paper reflects on the effectiveness of different types of urban metrics for describing particular aspects of urban form and provides an outlook on the added value of metric-based approaches for inter- and intra-urban analysis of urban form characteristics.

2. Materials and methods

2.1. Study area, data and pre-processing of data

Study area for this research is the Brussels Capital Region (Belgium). Originating in the Middle-Ages, the city of Brussels expanded rapidly during the 19th and 20th century. Nowadays, the Brussels Capital Region consists of 19 municipalities with a total area of 162 km^2, accommodating a population of 1.16 million (FOD Economie, 2014). To analyse the structure of the built-up area use was made of UrbIS 2012, the large-scale reference database of the region. Next to the built-up layer, including surface plots for individual buildings, a layer including boundary definitions of urban blocks was used to define the spatial units for morphological analysis. Most urban blocks are quite small, and, as such, can be assumed to be quite homogeneous in terms of morphological and functional characteristics. The Brussels study area consists of 4677 urban blocks, with an average size of 2.75 ha. In the analysis two versions of the built-up layer were used: one with individual buildings (original data layer) and one with all adjacent buildings dissolved into built-up patches. Both building layers include many small building structures that do not contribute to the characteristic form of individual urban blocks, such as garden houses, garages and small free-standing building extensions. To minimize the impact of these structures on metrics calculation, a simple iterative approach was used to filter them out prior to analysis (Vanderhaegen and Canters, 2010). The method ranks all building objects within an urban block based on size and iteratively takes out the smallest structure, using an appropriate threshold for the total built-up area to be removed within each block.

2.2. Composition of the urban fabric

Urban landscapes are shaped by the transport network, which defines the overall layout of the urban fabric, and are composed of four main components, i.e. the plot, the street, the built-up area and the open space (e.g. squares, parking lots, gardens, courtyards). Performing a detailed analysis of urban landscapes requires examining the size, shape and arrangement of individual elements of each type, as well as the spatial relationships between elements of different types (e.g. built-up versus open space), as these define the form of the urban fabric (Levy, 1999). Supplementary information can be gained through a further subdivision of each (main) component, and describing its sub-composition and sub-configuration. In the present study, the description of the urban landscape will initially be restricted to the distinction between the built-up area, defined as patches formed by adjacent buildings, and the open space area, defined as the collection of all natural and artificial areas within urban blocks not taken by buildings. Next, the built-up area will be described in more detail by subdividing it into individual buildings. More exhaustive descriptions of urban composition could be added by including detailed information on e.g. vegetation cover or use of different urban construction materials, as may be obtained from multi- or hyperspectral high-resolution remote sensing (Cavalli, Fusilli, Pascucci, Pignatti, & Santini, 2008), information on the three-dimensional structure which may be derived from 3D-city models obtained through the use of LiDAR technology (Zhou and Neumann, 2013), or a combination of both (Heiden et al., 2012). Although such a thematic refinement of one or more components of the urban landscape could be of interest for certain studies, e.g. ecological footprint assessment of the urban fabric at city block level, it is beyond the scope and the requirements of the present study.

2.3. Urban form and function

The morphological and functional characteristics of urban spaces can be categorised in various ways through the concept of zoning, a tool often used in urban planning where form, design and use of urban spaces is regulated through the definition of designated zones, on which specific restrictions apply. Whereas conventional Euclidean zoning focuses on a functional description of space, form-based codes prescribe the desired built-up form, which then results in a certain (mixture of) land-use(s) (Parolek, Parolek, & Crawford, 2008). From a purely functional perspective, a major distinction can be made between areas with residential function, non-residential function (commercial, industrial, services), green areas (e.g. parks, recreational areas, etc.) and areas linked to transport infrastructure (roads, railways, waterways and airports). While the use of urban spaces is not directly linked to their physical appearance, previous studies have demonstrated that the spatial pattern of land cover in urban areas, which defines urban form, can be related to an area's functional characteristics (Hermosilla, Palomar-Vázquez, Balaguer-Beser, Balsa-Barreiro, & Ruiz, 2014; Herold, Goldstein, & Clarke, 2003; Louw and Sithole, 2011; Yoshida and Omae, 2005). Inferring this relationship between urban form and function though is not a straightforward issue. Firstly, each type of land use can incorporate many types of urban form, characterised by varying densities and/or spatial configurations of the major urban landscape components, e.g. individual buildings may be adjacent or not, front and/or back gardens may or may not be present, etc. Secondly, many urban spaces have a multifunctional character, and, as such, some urban blocks could be best described as e.g. primarily residential, primarily commercial, while also including form characteristics typical for other land uses.

Based on theoretical models of residential urban morphology (Bürklin and Peterek, 2008; Panerai, Castex, Depaule, & Samuels, 2004), a typology consisting of six distinct and rather generic land-use/urban form (LUUF) classes was defined. The six LUUF-classes and their most important morphological characteristics can be described as follows:

1. *Commercial/industrial/services*: varying density of the built-up area, often comprised of few large individual buildings, sometimes positioned parallel to the transportation network, sometimes not (Fig. 1a);
2. *Mixed*: varying density of the built-up area, comprised of both large building structures and smaller buildings. In the case of high building densities, the block perimeter is often entirely built-up, while small (vegetated) open spaces may appear on the inner side of the block, functioning as courtyards and/or private gardens. If building density is lower, open spaces are often used as parking lots or gardens (Fig. 1b);
3. *Continuous residential without frontal setback*: dominance of continuous built-up area, consisting of long stretches of adjacent buildings along the urban block's perimeter. The composition of the inner side of the urban block can vary from small, non-vegetated courtyards to private vegetated gardens (Fig. 1c);
4. *Continuous residential with frontal setback*: dominance of continuous built-up area, consisting of long stretches of adjacent buildings parallel to the block's perimeter, yet with open space (vegetation/non-vegetation) in front of the buildings. The inner side of the urban block mostly consists of private gardens (Fig. 1d);
5. *Semi-detached residential*: clusters of adjacent buildings, often varying in number, parallel to the urban block's perimeter, surrounded by vegetated and small non-vegetated areas (Fig. 1e);
6. *Detached residential*: dominance of individual building units often oriented parallel to the urban block's perimeter, within a matrix of vegetated open space. Small non-vegetated areas may appear in the vicinity of building structures (Fig. 1f).

Although more specific types of (residential) urban form could have be defined, either related to the architectural characteristics of particular neighbourhoods, which can be linked to the various stages of urbanisation the city has been exposed to, or to specific, locally imposed spatial planning measures impacting urban form (Declève, Ananian, Anaya, & Lescieux, 2009; Dessouroux and Puissant, 2008), we opted for a more generic typology, as this will provide a better indication of the applicability of the approach proposed in other urban settings. For each of the six LUUF-classes, as described above, a set of 60 urban blocks was selected, based on visual interpretation of airborne imagery and cross-checking with information on the functional characteristics of the Brussels area (Dessouroux and Puissant, 2008) as well as with the development plan of the Brussels Capital Region. This set of blocks will be used as reference data for describing the morphological characteristics of the six LUUF-classes within the Brussels area (see further). Urban blocks containing less than 10% built-up area were considered as green areas (urban parks, very low density areas), and, therefore, were left out of the analysis.

2.4. Urban metrics

To quantify the urban form characteristics of each urban block, use was made of patch-based metrics originating from the field of landscape ecology, and of newly developed metrics describing the internal structure of the urban block along radial and contour-based profiles, as well as metrics describing building characteristics. All metrics defined can be categorised in terms of the specific aspects of urban form which they describe, i.e. density (dominance), size, fragmentation, shape

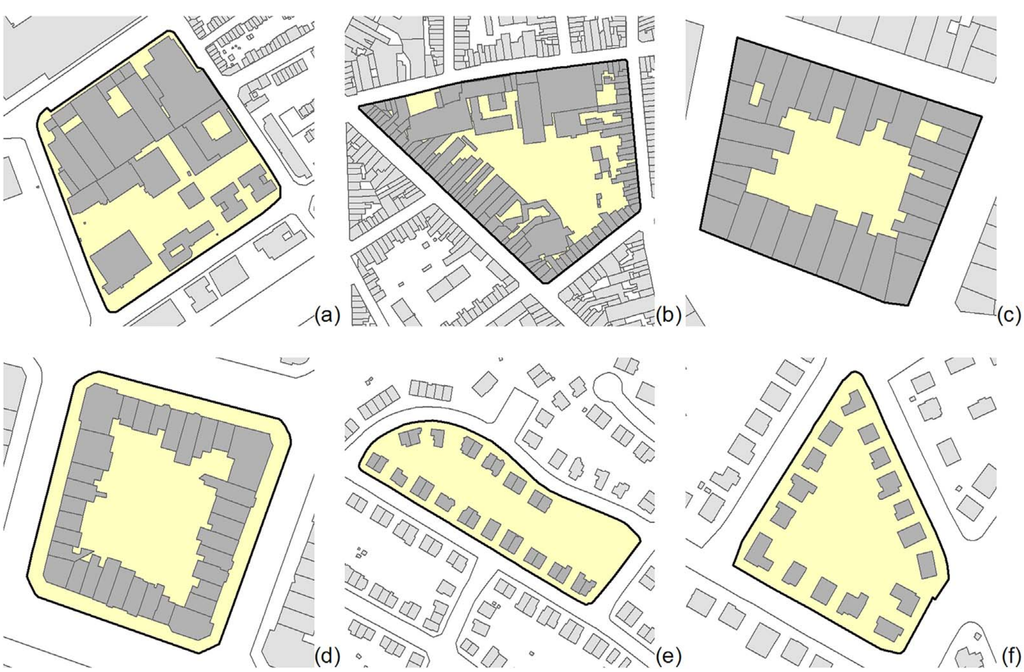

Fig. 1. Typical examples of the six LUUF-classes defined in this study: a) commercial/industrial/services, b) mixed, c) continuous residential without frontal setback, d) continuous residential with frontal setback, e) semi-detached residential, f) detached residential.

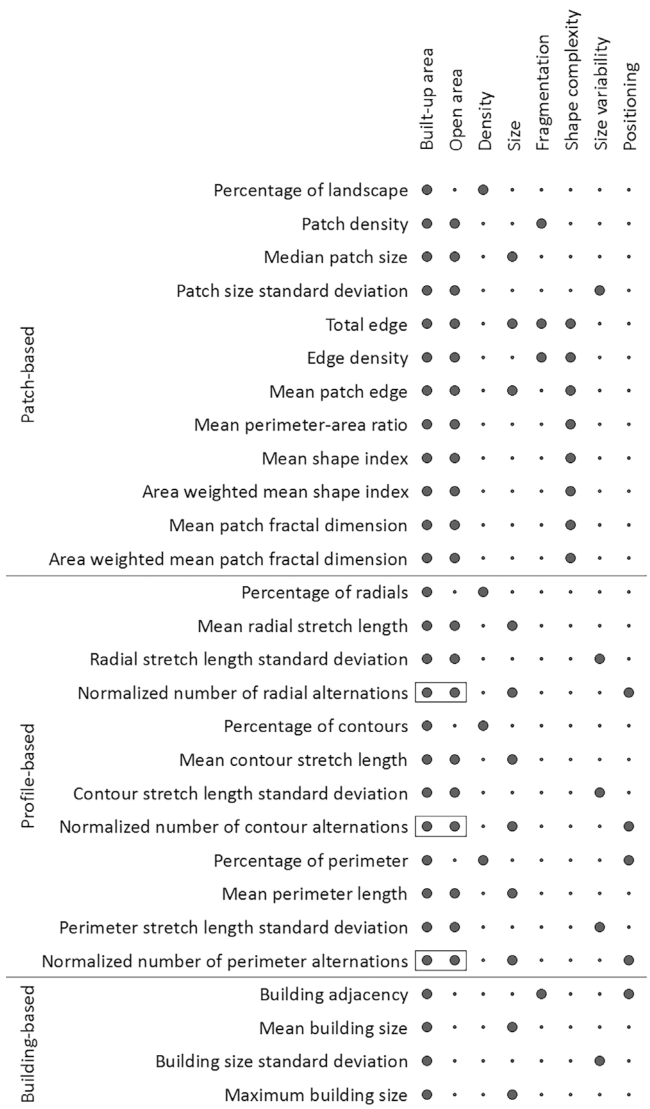

Fig. 2. Patch-based, profile-based and building-based metrics used in this study. For each metric it is indicated whether the metric has been calculated for the built-up area and/or the open area or for the combination of both, and which aspect(s) of urban morphology it describes.

complexity, variability in size and positioning (spatial arrangement of built-up and open space). Fig. 2 provides an overview of the metrics used in this study, grouped into patch-based, profile-based and building-based metrics, and indicates the aspect(s) of urban form each metric measures.

2.4.1. Patch-based metrics

Landscape ecological metrics (which we will further refer to as “patch-based” metrics) will be used to describe the characteristics of the built-up and open area within each block, where the patches constituting the built-up area will be defined as groups of adjacent buildings, while the patches constituting the open area will correspond to contiguous areas of open space (Fig. 3). They enable us to describe the area, size, shape characteristics and spatial arrangement of the “patches” within each block. For a formal definition of the patch-based metrics selected for our analysis (Fig. 2) the reader is referred to McGarigal et al. (2002). All metrics were calculated using Patch Analyst 5.1.

Although patch-based metrics are traditionally considered as describing one particular aspect of composition or spatial configuration, e.g. complexity, connectivity, etc., and are also grouped based on such criteria, metrics often describe more than one characteristic of the landscape at the same time, making a proper interpretation of the meaning of a particular metric not always easy. This is particularly the case for edge based metrics, which may provide an indication of size, fragmentation, as well as shape complexity (Fig. 2).

2.4.2. Profile-based metrics

As Fig. 2 shows, patch-based metrics mainly cover aspects of urban form related to the size, fragmentation and shape complexity of built-up and open space patches. Information regarding the spatial positioning of built-up and open space areas with respect to one another, or in relation to the block's perimeter (the street network) is lacking. To capture this information, we propose to describe the density, size, size variability and positioning of built-up and open space areas along radial and contour-based profiles. Radial metrics describe the occurrence of built-up and open space areas along a predefined number of radial transects defined through the urban block centre. Contour metrics do the same along successive contours drawn parallel to the urban block boundary and separated by a predefined distance (Fig. 3). Sequences of built-up and open space stretches found along these profiles can be described by their mean length, their length's standard deviation, and by the normalized number of alternations between built-up and open space along the profile. This results in the following metrics:

$$\textit{Percentage of radials/contours} = \frac{\sum_{j=1}^{z}\sum_{i=1}^{m_j} l_{ij}}{l_{tot}} \tag{1}$$

$$\textit{Mean radial/contour stretch length} = \frac{\sum_{j=1}^{z}\sum_{i=1}^{m_j} l_{ij}}{n} \tag{2}$$

$$\textit{Normalized number radial/contour alternations} = \left(\frac{\sum_{j=1}^{z}\Delta(BU\leftrightarrow OS)_j}{l_{tot}}\right) \tag{3}$$

$$\textit{Radial/contour stretch length standard deviation} = \left(\frac{\sum_{j=1}^{z}\sum_{i=1}^{m_j}(l_{ij}-\bar{l})^2}{n}\right)^{.5} \tag{4}$$

with z the number of profiles, m_j the total number of stretches of built-up or open space along profile j, l_{ij} the length of the i^{th} stretch of built-up or open space along profile j, n the total number of built-up/open space stretches along the profiles, $\bar{l}$ the mean radial/contour stretch length, $\Delta(BU\leftrightarrow OS)_j$ the number of alternations between built-up and open space along profile j and l_{tot} the total length of all profiles. The first metric measures the density (dominance) of built-up or open spaces along the profiles. In this study it is measured for the built-up space (the value for open space is the complement of the value for built-up space). The two metrics characterising the mean and standard deviation of the length of individual stretches of built-up or open space (2)(4) provide an indication of size and size variability along the profiles and may be calculated separately for built-up and open areas. Metric (3) focuses on the spatial arrangement of built-up and open spaces by calculating the number of times built-up and open space alternates while moving along the profiles, and then normalising this number of switches based on the total length of all profiles. As the structure of the urban fabric along the perimeter of the block is a prime characteristic of urban form, metric values for the contour profile corresponding to the block's perimeter are reported separately and are used as additional measures of urban form at block level (Fig. 2).

Based on sensitivity testing radial metrics were calculated using 16 profile directions, while contour metrics were obtained for a 10 m interval between two successive contours. Although the selective capturing of built-up and open space characteristics along radial, contour

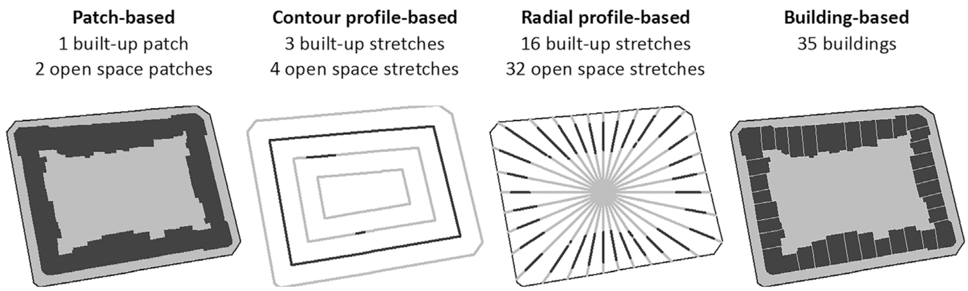

Fig. 3. Schematic representation of patch-, profile- and building-based metrics.

or perimeter profiles does not provide a complete description of the spatial arrangement of all the elements within an urban block, it is assumed that the combination of radial and profile based metrics is able to capture the spatial organisation of the urban fabric well, and should therefore also contribute to a better distinction between the different LUUF-types introduced earlier.

2.4.3. Building-based metrics

Next to the description of urban form in terms of the presence and spatial arrangement of built-up versus open spaces, vital information on urban form is also contained in the internal structure of the built-up area (Fig. 3). Therefore, metrics describing the size of individual buildings (mean size and maximum size) and the variability in building size (standard deviation) were also included in our analysis. Furthermore, the ratio between the number of buildings and the number of built-up patches, expressing the degree of clustering of individual buildings (building adjacency), can be considered a key feature of (residential) morphology, and was therefore also included in our list of metrics (Fig. 2).

2.5. Machine-learning-based LUUF-classification

Considering the complexity and the continuous nature of urban spaces, one may expect some overlap in urban form characteristics between different LUUF-types as defined in section 2.3, as well as a strong within-class variability. Machine-learning based classification approaches are considered as appropriate tools for coping with these type of complexities (Michie, Spiegelhalter, & Taylor, 1994). To assess the potential of patch-based, profile-based and building-based metrics, introduced above, for grouping urban blocks with different form and function, we therefore decided to make use of a classification tree approach.

Predictive classification trees are constructed by recursive orthogonal partitioning of the instance space based on attribute values (or a range of values), thereby relying on the information gain criterion, which evaluates the gain of a certain split-up for each possible (sub)set of instances (Quinlan, 1993). Recursive partitioning proceeds until each partition contains instances of a single class. Often, this results in very complex trees with low generalisation capacity. Therefore, classification tree algorithms offer the possibility to simplify the initial tree by replacing one or more subtrees by leafs, a process referred to as "pruning" (Michie et al., 1994). The result of pruning is often a more comprehensive tree, with a stronger capacity for generalisation, consequently yielding a higher classification accuracy. In this study use was made of the classification tree algorithm available in See5 (Quinlan, 1993).

Given the relatively small number of urban blocks used for training the classifier, and the large within-LUUF-class variation of metric values expected, the choice of training data used to construct the classification tree can be expected to have an impact on the metrics selected, their threshold values, the complexity of the classification tree and, as such, also on the predicted LUUF-class for unknown cases. All the more because the algorithm that partitions the instances is a so called greedy algorithm, i.e. once a group of cases is subdivided, the subdivision remains during further tree development. To assess this impact, bootstrap aggregation was applied (100 bootstrap samples, 1:1 ratio for training/test sample size). Applying bootstrap aggregation on the decision tree algorithm provides information on the frequency of use of each metric, i.e. the number of times a metric is selected throughout the hundred classification trees, and can be considered indicative of its importance. Based on the outcome of the ensemble of trees, the most frequently predicted LUUF-class for each urban block is assigned to the block. The frequency of prediction can be considered as an indication of the probability of the urban block being a member of a certain class or, in the context of the present study, the degree to which the block shares the typical urban form properties of that class. The latter can be related to the idea of an urban continuum, in which urban blocks may position themselves between LUUF-archetypes, e.g. urban blocks partly composed of detached and semi-detached buildings will be more likely to obtain lower probability values for the class they are assigned to, as they share properties of different classes. For each classification tree, the overall accuracy and producer's and user's accuracy can be derived based on the independent test sample. By assessing the distribution of overall accuracies and the producer's and user's accuracies for all bootstrap samples, a robust performance assessment is obtained of the way the classifier, and the metrics it makes use of, succeed in assigning urban blocks to the proper LUUF-class.

To assess the potential of profile-based metrics, and of information carried by data on individual building delineation, for describing the typical urban form characteristics of the different LUUF-types identified in this study, the classification approach described above was applied in three steps. In the first scenario, only traditional landscape ecological metrics ('patch-based') were included in the analysis. Secondly, all profile-based metrics were added to the initial set of patch-based metrics, whereas in the third scenario also building-based metrics were added (Fig. 4). The frequency by which metrics are selected throughout

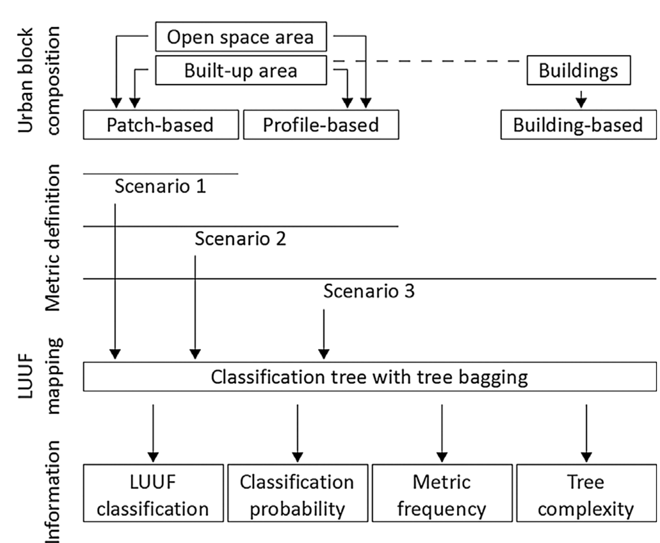

Fig. 4. Overview of land-use/urban form classification and validation workflow.

Fig. 5. Frequency of occurrence of urban metrics in the classification trees, for each scenario. Frequencies shown in brown point to urban metrics referring to both the built-up and open space, or to urban metrics calculated for the built-up space as the complement of open space.

the three scenarios provides an indication of how important these metrics are for describing urban form characteristics that allow distinguishing between the different LUUF-types considered. Changes in classification accuracies and classification probabilities from one scenario to the next provide an indication of the relative contribution of profile- and building-based urban metrics to the description of the urban form types, as defined in this study. Finally, the number of branches and unique metrics incorporated in each tree is indicative of the included metrics' capability to capture morphological information specific to each LUUF-class.

3. Results

3.1. Metric's frequency and tree complexity

Quantifying urban structure solely by means of traditional patch-based metrics (scenario 1) results in a high number of metrics that are frequently selected (Fig. 5). The three most selected patch-based metrics are the *area weighted mean patch fractal dimension*, the *mean patch edge* and the *mean shape index*. A dominance of patch-based metrics describing the built-up area compared to open space metrics can be observed. Except for the *median patch size*, all patch-based metrics describing built-up space are selected more often than their open space equivalent. The percentage of landscape taken by the built-up area is ranked − contra-intuitively − only ninth. However, its selection frequency, and that of other metrics ranked lower, remains relatively high. The high frequency selection of all patch-based metrics also reflects in the complexity of the classification trees, with a median value of 16 split-ups and 12 unique metrics incorporated (Fig. 6).

It should be noted that some patch-based metrics measuring similar

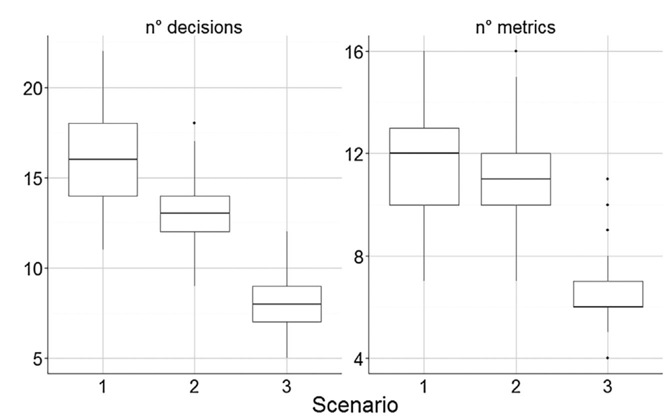

Fig. 6. Boxplot visualisation of the number of decisions and the unique number of metrics used, for each scenario.

characteristics of urban form show relatively high correlations (e.g. mean perimeter-area ratio and mean patch fractal dimension for built-up area, mean patch edge and median patch size for open area). This correlation may affect the frequencies obtained for these metrics as reported in Fig. 5, in the sense that the frequencies for two correlated variables will likely be lower than if only one of these variables would be included in the modelling. While we might have removed some of the variables to avoid this effect, when analysing the correlation between similar variables for observations belonging to each of the LUUF classes separately we noticed that correlations were often not as high as overall statistics indicated. This implies that by reducing the set of variables there is the risk of removing a variable that might be important in distinguishing one particular morphological class from the other classes, with negative impact on classification accuracy. As such we decided to keep all metrics in the analysis. Taking the above into account, frequencies in Fig. 5 should not be interpreted as an indication of the importance of each individual variable in the classification process, but rather as an indication of the importance of measuring particular aspects of urban form for LUUF discrimination, as described by the metrics selected.

The inclusion of profile-based urban metrics results in a reduced selection of patch-based metrics, some of them to less than half or even one-third of their frequency in scenario 1 (Fig. 5). As in scenario 1, the most frequently used patch-based metrics are related to the shape complexity of the built-up space, an aspect of the urban landscape not covered by profile-based metrics. Information related to size (*mean contour stretch length*), size variability (*contour stretch length standard deviation*) and density (*percentage of perimeter*) are most frequently described by profile-based metrics. Regarding the open space, a patch-based description of shape complexity and fragmentation (*edge density*, *total edge* and *mean shape index*) and size (*median patch size*) contribute most to the distinction of LUUF-classes. Nevertheless, a clear decrease in the use of open space patch-based metrics is observed. The inclusion of alternative metrics, which describe the urban structure along radial, contour and perimeter profiles results in a slight decrease of the number of metrics selected (a median of 11 unique metrics compared to 12) and a more outspoken decrease of tree complexity (a median of 13 split-ups compared to 16) (Fig. 6).

All patch- and profile-based metrics become less important as discriminating variables when information about individual buildings is included in the urban form description (scenario 3). Except for *percentage of perimeter*, which comes close to its frequency of scenario 2 and is used in most of the classification trees, and *mean patch edge* of built-up area, which shows up in about one third of the runs, patch- and profile-based metrics hardly seem to contribute to distinguishing between the different LUUF-types (Fig. 5). This is also reflected in a further simplification of classification trees and their incorporated metrics (a median of 8 split-ups and 6 unique metrics) (Fig. 6).

3.2. LUUF classification accuracies

In spite of the complexity of classification trees obtained for scenario 1, classification accuracy can be considered low, with a median overall accuracy of 64.4% (Fig. 7). Lowest median producer's and user's accuracies are observed for *mixed* (46.3% and 47.7% respectively) and *semi-detached residential* (57.8% and 58.3% respectively), whereas highest median producer's (79%) and user's accuracies (80%) are observed for *continuous residential without frontal setback*, followed by *detached residential* (72.4% and 73.3% respectively). While for scenario 2 tree complexity and the number of unique metrics incorporated are reduced (Fig. 6), overall accuracy increases to 72.2% (+7.8%). Together with the observed shift in metric selection, the increase of the median producer's and user's accuracy with 6–13% for most LUUF-classes, and in particular for the problematic *semi-detached residential* class in scenario 1, points out the added value of profile-based metrics. An exception to this overall rise in accuracy is the *commercial/industrial/services* class, with a nearly unchanged producer's accuracy, and the *mixed* class, with an unchanged user's accuracy. A further improvement of 12.2% of the median overall accuracy (84.2%) is observed for scenario 3. For overall accuracy, as well as for PA and UA of most classes, the interquartile range is lowest in scenario 3. Including information on individual buildings results in satisfactory (≥85%) median producer's and user's accuracies for *commercial/industrial/services*, *continuous residential with and without frontal setback* and *detached residential* classes. The largest increase of median user's and producer's accuracy is observed for the *commercial/industrial/services* (+17.4% and +20.0% respectively) and *mixed* class (+19.5% and +20.0% respectively).

3.3. LUUF mapping

The LUUF-map for the Brussels Capital Region, obtained by assigning each urban block to its most frequently occurring LUUF-class using bootstrap aggregation under scenario 3, is shown in Fig. 8. Green area blocks, i.e. less than 10% of their surface is taken by built-up area, which were excluded from the analysis, are mainly situated in the urban fringe (Sonian forest, very low-density urban blocks), and in the green parks throughout the Brussels Capital Region. *Commercial/industrial/services* urban blocks are found along the industrialized canal zone, in the business district close to the railway station just north of the centre (Gare du Nord), along the "north-south" axis connecting the Gare du Nord with the Midi railway station, along the administrative zone connecting the parliament area with the European quarter and in the university area, southeast of the Brussels' pentagon. The class is also omnipresent along the E40 highway east of the city, around the airport and in the Heizel area. Despite their strong presence in the urban tissue, *commercial/industrial/services* blocks only represent approximately one-eighth of all urban blocks (11.4%).

Except for a few blocks situated in the city centre (pentagon), *continuous residential* blocks *without frontal setback* appear mostly in the 19th century expansion belt around the centre. Moving from the city centre towards the urban fringe, a transition is noticed from *continuous residential without frontal setback* to *continuous residential with frontal setback*, to *semi-detached residential*, and finally to *detached residential*. More than two-third of all urban blocks are labelled residential, more than half of them are *continuous residential without frontal setback* (37.6%), followed by *semi-detached residential* (13.1%), *continuous residential with frontal setback* (7.8%) and *detached residential* (4.0%). The relatively high density of the Brussels Capital Region and the exclusion of very low density blocks from the analysis explains the limited presence of the latter class in comparison to the other LUUF-classes. Mixed urban blocks (18.6%) appear throughout the entire Brussels Capital Region, with higher concentrations found within the city centre and along the central lanes radiating from – and parallel to – the

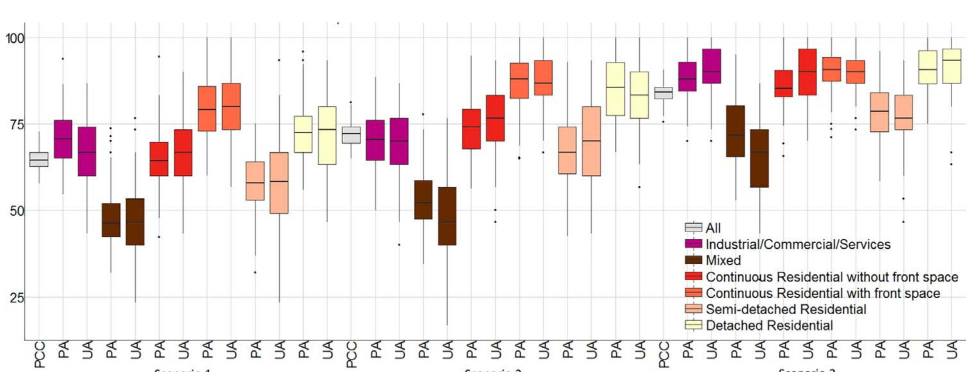

Fig. 7. Boxplot visualisation of the obtained percentage correctly classified blocks (PCC), and LUUF-class specific producer's (PA) and user's accuracies (UA), for each scenario.

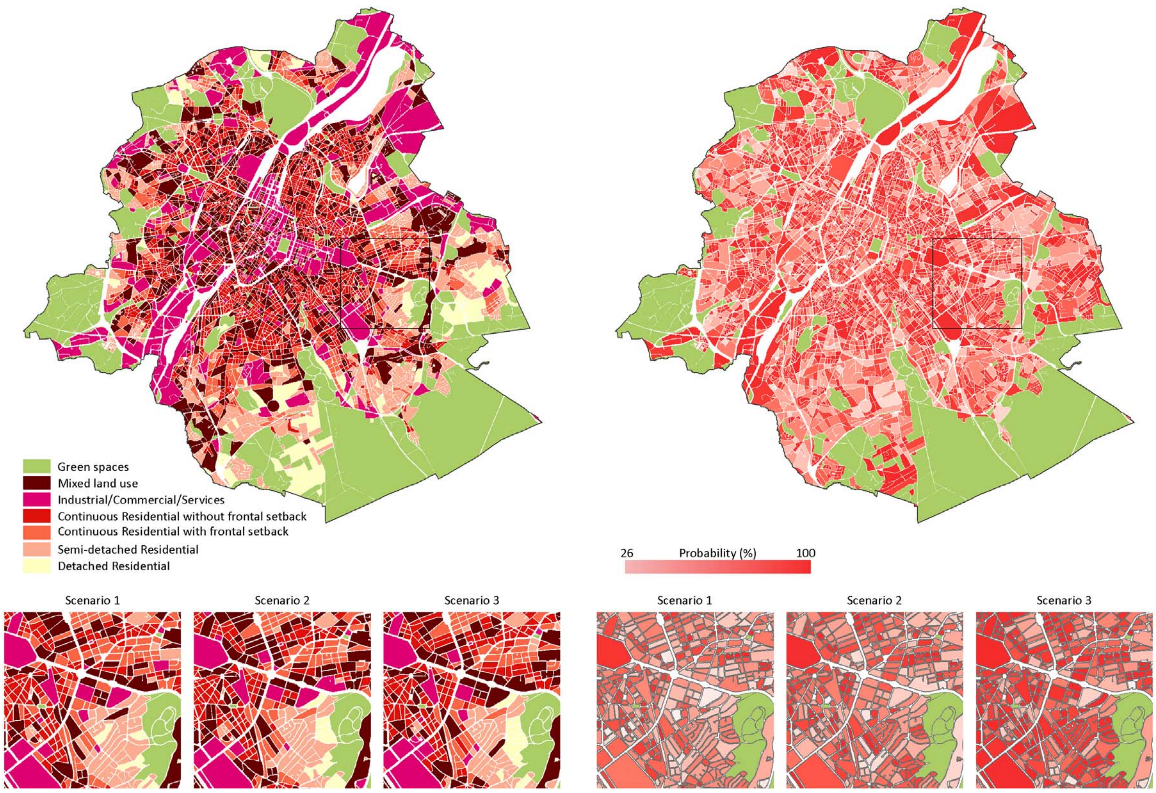

Fig. 8. LUUF map of the Brussels Capital Region obtained by selecting the most frequently assigned LUUF-class for each urban block, using scenario 3, and corresponding classification probabilities. Enlargements below show the classification behaviour and corresponding classification probabilities for a subset of the study area, located at the urban fringe.

pentagon.

3.4. LUUF classification probabilities

Next to an improved overall accuracy, the inclusion of profile-based metrics and information on individual buildings results in an increased occurrence of high(er) classification probabilities (Fig. 9). Whereas scenario 1 shows a steady increase of probability densities in the low probability range, medium and higher probability values all show similar densities. Probability values for scenario 2 show lower densities for low and medium values, and higher densities for high probability values. A similar trend, although much more outspoken, can be observed for scenario 3, where 56.9% of all urban blocks are assigned to a LUUF-class with a classification probability value of at least 90%, and more than three-quarters (75.8%) of the urban blocks are labelled with a probability value of at least 70%. Observing the spatial distribution of probability values in relation to the LUUF labelling (Fig. 8) reveals a class-dependency. Although the full range of probability values can be found in each LUUF-class, *detached residential*, *continuous residential without frontal setback*, and *commercial/industrial/services* blocks mostly show higher probability values. Visual comparison of classification probabilities for the three scenarios in relation to the assigned LUUF-class shows a strong increase in classification probability for *commercial/industrial/services* and *(semi-) detached residential* urban blocks from scenario 1 to scenario 3, whereas low classification probabilities are observed for urban blocks for which the assigned LUUF-class alternates based on the applied scenario.

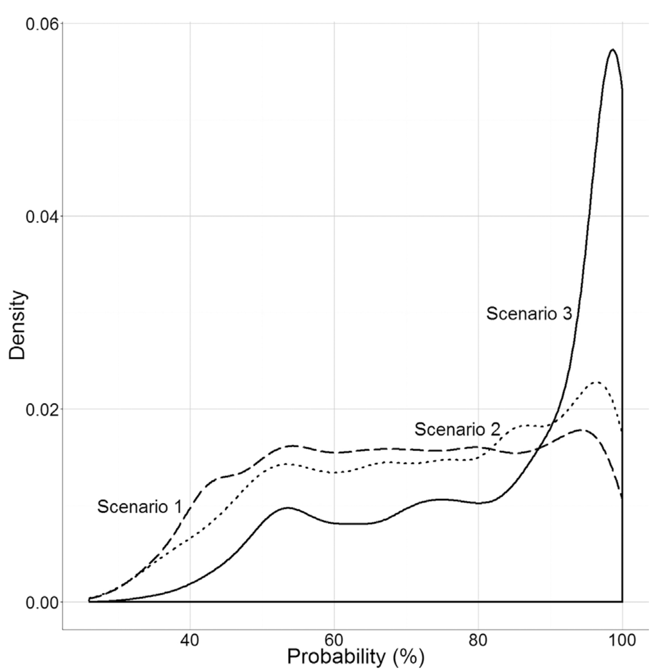

Fig. 9. Density of classification probabilities, for each scenario.

4. Discussion

4.1. Effectiveness of urban metrics for describing urban form at block level

The high selection frequency of most patch-based metrics in scenario 1, in combination with the complexity of the constructed classification trees and the (low) classification accuracies obtained, is indicative of the difficulty involved in trying to describe essential aspects of urban form by means of traditional landscape ecological metrics. Notwithstanding the high selection frequency of *percentage of landscape*, distinctive information appears to be mostly contained in configurational aspects (shape characteristics) of the urban landscape. The wide range of built-up densities within each LUUF-class is a plausible cause for this. The relatively low accuracies obtained in scenario 1 – only for *continuous residential* blocks *with frontal setback* the median user's and producer's accuracy lies around 80% – points out the ineffectiveness of patch-based metrics for describing the urban form characteristics of the LUUF-classes considered in this study.

The reduced complexity of classification trees (decreasing number of decisions and unique number of metrics) in scenario 2, and the increased classification accuracies obtained, demonstrate the added value of profile-based metrics for capturing essential information on urban form. A strong reduction of the selection frequency of patch-based metrics related to aspects of density, size and size variability is observed. Those aspects are, in scenario 2, covered by the profile-based metrics *percentage of perimeter*, *mean contour stretch length* and *contour stretch length standard deviation*. The fact that the contour/perimeter-based metrics just listed are more frequently selected than metrics based on radial profiles indicates that a contour-based description of urban form is more effective in describing the spatial configuration of different LUUF-types than the use of metrics based on radial profiles. In both scenarios 1 and 2, a preference of urban metrics describing the built-up space over their open space counterparts is notable. This preference for built-up metrics is, except for the *mean perimeter length*, even more outspoken for profile-based metrics. It indicates that the structure of the built-up area contributes most to the differentiation between the LUUF-types considered. The latter could have been expected given the way the different LUUF types in this study have been defined and corresponds with the notion that in the analysis of urban form the built-up area is usually considered as figure, while open spaces define the background or the matrix in which the built-up area is embedded.

Patch-based and profile-based urban form analysis, as applied in this study, solely relies on the distinction between built-up space and open space at urban block level. While in this study the positioning of built-up versus open space was obtained from a large-scale building database, the approach proposed here also lends itself well to urban form analysis from high-resolution remotely sensed data. The latter may be particularly useful in cases where no large-scale reference data on the built environment is available, or if one wishes to perform urban form analysis in the context of urban monitoring (time series analysis) or interurban comparison (see also below), and has to rely on remotely sensed data as the sole data source. Discriminating between built-up and open space using multispectral data is quite easy in the case where open space is covered by vegetation. The only drawback of having to rely on remotely sensed imagery is that depending on the type of spectral data used (spectral range and resolution) it may be difficult or even impossible to separate buildings from non-green, spectrally similar open spaces like parking lots, walking or cycling paths, or stretches of bare soil (Dengsheng, Hetrick, & Moran, 2011; Weng, 2012). As such urban form analysis from remotely sensed data will often have to be based on the distinction between green and non-green spaces, rather than on the distinction between open and built-up spaces like in this study. While much work has already been done on remote sensing based analysis of urban form, most of this work relies on the use of patch-based metrics originating from landscape ecology (Herold, Scepan, & Clarke, 2002; Lv et al., 2012; Ramachandra, Bharath, & Durgappa, 2012). Given the limitations of this type of metrics for characterising intra-urban form at block level, it would be interesting to apply profile-based metrics as introduced in this study for improving remote sensing based urban form analysis.

Despite the noticeable improvement of classification accuracy for most LUUF-classes when using profile-based metrics in combination with patch-based metrics, for some LUUF types – more in particular *commercial/industrial/services*, *semi-detached residential* and *mixed* – classification accuracies remain relatively low (around 75% or lower). This points out the difficulty, also when using profile-based metrics, of capturing important information contributing to a proper characterisation of these classes. The information that is notably missing pertains to the internal structure of built-up patches, and requires data on the number and size of individual buildings within each patch. Including building-based metrics allows one to capture the wide range of structural variety that is present in *commercial/industrial/services* and *mixed* blocks and to identify the typical form of the *semi-detached* blocks, whose main characteristic is the specific spatial arrangement of individual buildings composing the built-up area.

Moving from scenario 1 to scenario 3, the trend towards less complex classification trees, composed of fewer unique metrics, the shift towards higher classification probabilities and the evolution of overall accuracies and LUUF-class producer's and user's accuracies points to an increased effectiveness to capture and quantify distinctive features of the defined LUUF-classes. At first, this is achieved by introducing a profile-based description of the urban landscape and subsequently by including information on individual buildings constituting the built-up area. It should be kept in mind though that the performance of the metrics and their ability to describe and distinguish between different LUUF-classes will depend on the choice of the study area and the defined LUUF-typology. In this study, we deliberately opted for a rather generic, not too context-dependent LUUF-typology that might be easily applicable to other cities with similar urban structure. Applying the proposed classification strategy on other urban areas, and comparing the median value and the range of values of key metrics for each LUUF type, might provide a useful framework for interurban comparison (see also below). Alternatively, one might also consider applying the type of metrics proposed in this study in combination with a more elaborate and/or more context specific LUUF typology, and/or expand the conceptual model that is used as a basis for describing the urban landscape through a further subdivision of urban landscape components (e.g. vegetated versus non-vegetated open space, functional or structural description of individual buildings, …) (see also 2.2). This might require the definition of additional urban metrics able to describe the spectrum of urban form characteristics envisaged.

4.2. Towards a metric based approach for describing urban form

In each of the three scenarios, lowest classification accuracies are obtained for *mixed* and *semi-detached residential* urban blocks. These two LUUF-types can be considered as 'in-between' classes, mainly sharing characteristics of *commercial/industrial/services* and *continuous residential* blocks *without frontal setback*, and of *continuous residential* blocks *with frontal setback* and *detached residential* blocks respectively. This is illustrated in Fig. 10, which shows bi-variate plots for a selection of urban metrics indicating the position of the reference urban blocks for each LUUF-class (in color), as well as all other blocks constituting the Brussels Capital Region (shown in the background). The metrics used for constructing the plots have been chosen based on their frequency of inclusion in the classification trees in each scenario, and the different aspects of urban form which they represent (Fig. 5). The plots reveal a large within-class variation in metric values for some LUUF types. This is particularly the case for the *industrial/commercial/services* and *mixed* urban blocks. Residential urban blocks appear more clustered, with *detached residential* and *continuous residential* blocks *without frontal setback* being positioned at the extremes of a residential continuum. In between, for several metrics a clear transition from *detached residential* to *semi-detached* and then to *continuous residential* blocks is observed. Although reference blocks for each LUUF class (except the *mixed* class) show clear patterns of concentration on some metrics, the assembly of all urban blocks results in one continuous LUUF space, confirming the earlier suggested presence of an urban continuum. It may therefore be more appropriate to consider each urban block as taking up a unique position in a multidimensional space defined by a set of relevant urban form characteristics describing this urban continuum. In this approach, each neighbourhood with archetypical LUUF-characteristics as well as each urban block with characteristics deviating from these archetypes can be positioned within this continuum.

Complementing the traditional approach, where urban space is considered as a spatial realisation of a discrete set of urban form types –

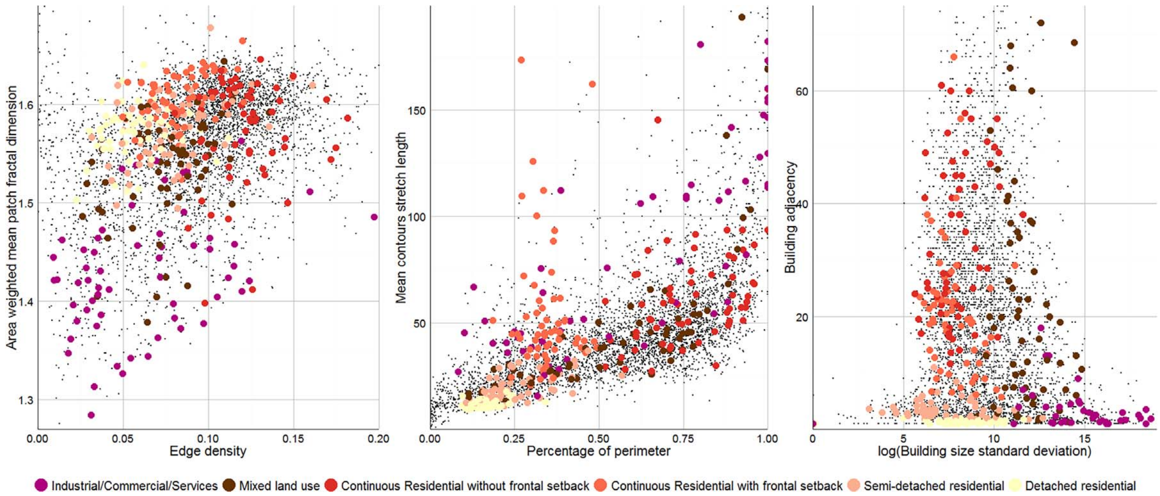

Fig. 10. Illustration of the urban continuum for a selected set of urban metrics, representing different aspects of urban form. Coloured dots represent the urban blocks used to train and validate the classifier, black dots represent the remaining urban blocks in the study area.

often linked to form-based or use-based zoning or a combination thereof – a metric-based approach enables a more continuous description of urban form, better able to deal with the intrinsic complexity of urban spaces. The concept of a multi-dimensional urban continuum, defined by a set of key metrics describing essential characteristics of urban form offers interesting prospects for intra- and interurban comparative analysis of urban areas, and for monitoring spatio-temporal characteristics of particular aspects of urban form.

5. Conclusion

In this paper, the use of spatial metrics for quantifying key morphological characteristics of the urban fabric, and for mapping distinct types of urban form and function, has been investigated. To describe urban form at city block level, traditional landscape ecological metrics were combined with newly proposed profile-based metrics, providing a more explicit description of the spatial arrangement of open and built-up spaces, and with metrics describing the main characteristics of individual buildings. Use of the metrics for distinguishing distinct LUUF-classes was tested on the Brussels Capital Region, by using a decision tree classification approach in combination with bootstrap aggregation. Increased overall and class-specific classification accuracies, classification probabilities and a reduced tree complexity are obtained when the traditional patch-based metrics are used in conjunction with the profile-based and building-based metrics, pointing out the effectiveness of the proposed metrics to capture the essential form characteristics of the LUUF-classes considered.

Metric-based approaches for describing urban form offer interesting prospects for spatio-temporal monitoring of urban spaces, as well as for comparative urban studies. Developments in 3D-city modelling, enabling the third dimension to be included in urban form analysis, is one of the possibilities to extend the LUUF-typology applied in this study. Additionally, describing the composition and spatial arrangement of the urban green component by using remotely sensed data may form the basis of urban form descriptions more geared towards ecologically oriented studies. Rather than considering urban spaces as the physical realisation of a discrete set of urban form types, it would also be interesting for future research to focus more on the use of urban metrics for defining continuous representations of urban form, and to use the concept of an urban continuum as a basis for intra- and interurban analysis of urban form.

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