The urban form of Brussels from the street perspective: the role of vegetation in the definition of the urban fabric

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Abstract

In the context of rising interest in the impact of the urban environment on human well-being, appropriate modeling of the urban landscape needs to be developed. Traditional analyses from the aerial point of view are not suitable; it has become essential to consider the pedestrian perspective. The Multiple Fabric Assessment (MFA) is a recent protocol that provides morphological clusters of urban fabric by incorporating a street perspective into a Naïf Bayesian clustering analysis. We apply the protocol to all street segments in Brussels. We first investigate the role of vegetation and areas devoted to pedestrians in the identification of urban fabric. We show that incorporation of these measurements into the MFA allows of better definition of the urban fabric in suburban areas, demonstrating how vegetation has become fundamental to the description of residential neighborhoods, while it has a less relevant role in defining the urban fabric in compact central areas. We then identify twelve meaningful clusters of urban fabric in Brussels and link them to the different urban development phases. Particular attention is paid to Brusselization in the city center and garden districts in the suburbs. The results provide clear definition and clustering of streetscapes in an urban environment, a stepping stone via which future research could cross-analyze the relationships between well-being and built forms.

Research highlights

- The MFA protocol is a very useful tool for partitioning the urban fabric from a pedestrian point of view.
- Its application to Brussels leads to a spatial partitioning in line with the urban development history of the city.
- Vegetation is essential in the definition of urban fabric and adds a valuable perspective to streetscape analysis.

1. Introduction

Urban landscapes are the backdrop of life for 55% of the world's population, and this number is expected to increase (United Nations, 2018). Streets, squares, parks, and gardens are traditionally identified as public spaces where urban outdoor activities take place (Gehl, 1987). The surrounding urban landscape influences how city users perceive the urban space and, ultimately, their behavior, activities, and well-being (Jacobs, 1961). Several features of urban morphology, such as building height, daylight, built-up density and presence of sidewalks, and their impacts on human behavior, have been individually explored in the scientific literature (Evans, 2003; Rao et al., 2007; Sullivan & Chang, 2011). Likewise, more recent studies have investigated the beneficial effects of vegetation distribution and accessibility on psychological, emotional and mental health (Herzele & Vries, 2012; Beyer et al., 2014; Alcock et al., 2014). The link between urban environment and human well-being is a growing field of research, requiring the development of new tools, data and models.

Starting from the 1950s, urban geographers, morphologists and designers have produced a wide-ranging literature proposing different approaches to analyzing the urban form and identifying typo-morphological urban regions (Vernez Moudon, 1997), and this activity has intensified over the last 20 years with the increasing use of Geographic Information Systems. Within this research domain, an increasing number of papers propose more or less sophisticated computer-aided procedures to enable the development of quantitative analytical approaches for the study of the urban form and its relationships with human-related phenomena (Berke & Vernez-Moudon, 2014; van Kamp et al., 2003). These approaches depend on the study context, the geographical scale, the indicator types (including objective or subjective measurements), and the time frame. More specifically to the urban form, the indicators depend on the *register* of the urban form concerned (Fusco, 2018; Levy, 2005), the metrics implemented (single or multiple), and the point of view from which the form of the physical city is observed (Araldi & Fusco, 2019).

When focusing on analysis of the urban form – the spatial organization of urban physical elements such as buildings, streets and parcels – several methods have been developed, such as: street-network configurational analyses (Hillier, 1996; Porta et al., 2006), fractal-based approaches (De Keersmaecker et al., 2003; Thomas et al., 2008), multivariate analysis of morphometric descriptors of built-up density (Berghauser Pont & Haupt, 2010), or a combination of geoprocessing and spatial statistic procedures (Caruso et al., 2017). Data can be very simple, such as the centroid of each building (Caruso et al., 2017; Thomas et al., 2008) or the building footprint (Hamaina et al., 2014), or include several morphological indicators (Araldi & Fusco, 2019; Gil et al., 2012; Vanderhaegen & Canters, 2017).

While these studies allow quantitative description of the urban form, two aspects are traditionally overlooked. Firstly, the pedestrian point of view: when analyzing socio-economic phenomena occurring in the public space, the pedestrian perspective assumes crucial importance and should be preferred to the more aerial point of view traditionally favored in urban studies (Araldi & Fusco, 2019). Secondly, public and private green spaces feature in the definition of urban morphology indicators and, consequently, in the urban fabric.

The importance of the urban form from the street perspective has already been recognized by several authors. From the urban design field of research, Purciel (2009), Vialard (2013) and Harvey et al. (2017) provide innovative protocols for quantitative analysis of the distribution of urban features along the edges of streets, i.e. the skeletal streetscape. Araldi & Fusco (2019) extended the analysis of the urban form of individual streetscapes to the analysis of urban fabrics and morphological regions using the Multiple Fabric Assessment (MFA) protocol. MFA allows both the characterization of individual morphometrics at street level and the identification of urban fabrics as perceived by pedestrians within large urban areas. This approach differs strongly from the aerial approach traditionally adopted by urban planners, geographers and morphologists: urban morphological features are described quantitatively from the pedestrian point of view and their spatial distribution is statistically evaluated in order to identify significant local patterns in the street-network layout. Lastly, patterns of morphological indicators are combined using Naïf Bayesian Classification approaches, allowing a probabilistic description of urban fabric profiles.

While the importance of vegetation distribution in urban public spaces has been widely investigated in quantitative analyses (e.g. Harvey et al., 2017; Li et al., 2015), urban form studies have focused on built-up rather than green spaces. There are some exceptions such as Hermosilla et al. (2014), who included vegetation cover data obtained from high-resolution satellite imagery and LiDAR to define urban typologies. Vegetation indicators such as these require specific data, either pre-processed or from high-resolution satellite imagery, in order to have a fine-grained definition of vegetation. There is also a rising interest among streetscape researchers in vegetation and built-up indicators based on street images (e.g. Google Street View), which provide realistic 3-D representations of urban streets from a pedestrian's perspective (Gong et al., 2018; Li et al., 2015; Richards & Edwards, 2017). The problem with all these vegetation data is that the choice of database significantly affects the modeling results (Texier et al., 2018; Trabelsi, 2020).

We focus here on the Brussels-Capital Region (BCR), Belgium. Modeling of intra-urban fabrics has already been carried out in relation to this study area (e.g. Vanderhaegen & Canters, 2017), but with different goals, data and tools. In this paper our goal consists in identifying urban morphological regions (defined in terms of a given urban fabric), as in the traditional urban typo-morphological approach. While Vanderhaegen and Canters (2017) analyzed the urban form from the traditional planar point of view on the basis of an urban street-block partition, in this paper we will adopt the pedestrian perspective by our use of the MFA protocol. Furthermore, specific pedestrian and vegetation features of the urban form are specifically developed and introduced in the original MFA protocol. Use of this procedure in the case study of the BCR allows us to observe the role played by vegetation in the identification of urban fabrics.

The paper is organized as follows. After the study area description (Section 2), the main steps in the MFA protocol are presented, including the innovations in the context of the BCR in Section 3. A specific focus is then placed on the role of vegetation in the definition of the urban fabric: the MFA protocol is implemented both with and without vegetation indicators in order to identify the role of vegetation in defining the urban fabric. Our results are presented in Section 4, and Section 5 concludes the paper.

2. Study Area

Brussels is the capital of Belgium, centrally located in the country. The city extends into three administrative regions: the Brussels-Capital Region (BCR), Flanders and Wallonia. There is no official definition of the 'urban agglomeration'; its delineation depends strongly on the indicators and methods used (Thomas et al., 2012). We focus here on the urban area encompassed within the administrative border of the Brussels-Capital Region (BCR). This choice limits problems arising from inter-regional data comparison by allowing the use of well-established and consistent databases: the Urbis open database (BRIC, 2017) and remotely sensed vegetation data (Van de Voorde et al., 2010) [Fig. 1].

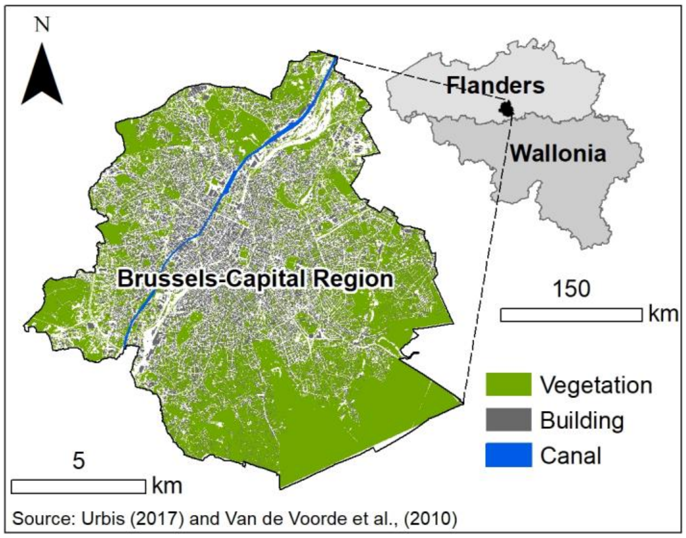

Fig. 1. *Brussels-Capital Region: relative location in Belgium and built-up composition*

The BCR is divided into 19 municipalities. It covers 161.38 sq. km and has 1.2 million inhabitants (source: Statistics Belgium – 01/01/2018), which means an average density of 7,438 inhabitants per square kilometer. For the sake of simplicity, the BCR will henceforth be referred to in this paper as Brussels.

The current urban fabrics in Brussels and their spatial organization result from the long historical evolution of the city. The core of the city presents the oldest vestiges of the original settlement, enclosed within two successive ramparts (8th and 14th centuries) that can still be distinguished in the street pattern. Surrounding the historical center, the first concentric expansion dates back to the 19th century and is characterized by the typical Brussels townhouses: contiguous bourgeois family houses. These are recognizable by their limited width (~6 m) and *bel étage* (*piano nobile*), which is generally raised by 1.80 m above the sidewalk level. This creates a distance from the public street and also provides lighting in semi-basement spaces (Ledent, 2017). This type of building is still a particular feature and a specific part of the identity of the Brussels urban landscape. At the beginning of the 20th century, the development of garden districts (inspired by the English garden cities) shaped some of the fabric of the suburbs. And since that same period, Brusselization has reshaped part of the central area as a result of the great increase in tertiary employment and the consequent new buildings and fabrics (De Beule & Dessouroux, 2011).

The vegetation in Brussels is not only a feature of the garden cities: it represents 54% of the BCR surface (Van de Voorde et al., 2010); this includes public parks and recreation areas and urban forests, as well as private gardens and estates.

Analysis of the urban morphological characteristics of Brussels has already been carried out by several authors. De Keersmaecker, Frankhauser and Thomas (2003) used fractal dimensions from a grid to highlight the spatial patterns of the multi-level building structure. More recently, Vanderhaegen and Canters (2017) computed urban metrics on city blocks to identify distinct types of urban form and function. In focusing on the spatial distribution of the Brussels green spaces, we might mention the studies of Stessens et al. (2017) and Van de Voorde (2017), in which several indicators of distribution, quality and accessibility to green spaces are suggested. Beyond these scientific studies, we might also consider the European project Urban Atlas, which is available for Brussels. Much more precise than CORINE land cover, it allows detailed and comparable classification of land use in European cities, but lacks the specifics of urban morphometrics.

As highlighted in the previous section, despite the great value of these studies in describing the urban form of Brussels using different approaches and emphases, they do not incorporate the pedestrian perspective into their analysis and they consider the distribution of vegetation and built form separately, without taking account of their combined effect on the definition of the urban fabric.

3. Method

Araldi and Fusco (2019) developed the Multiple Fabric Assessment (MFA) protocol for the identification and characterization of urban fabrics. This is a data-driven bottom-up procedure which could be summarized in four steps [Fig. A1, in the Appendix]. After definition of a street-based spatial unit partition – the Proximity Band (PB) (Section 3.1) –, urban form indicators are computed via geoprocessing protocols which capture different aspects of the skeletal streetscape (Section 3.2). Spatial patterns of morphological indicators are identified in a network-constrained environment (Section 3.3). Finally, local patterns are clustered using a Naïf Bayesian classification approach (Section 3.4). The MFA allows the urban landscape to be described at both the individual level (streetscape) and the meso-scale level (urban fabric).

This method has proved successful in the analysis of several case studies with different geographic extent and data sources: the French Riviera conurbation (Araldi & Fusco, 2019), the metropolitan region of Osaka-Kobe, Japan (Perez et al., 2019) and the Karşıyaka district, Turkey (Erim, Araldi, Fusco & Cubukcu, unpublished data). It is applied here to the intra-urban environment of Brussels.

3.1. Basic Spatial Unit: the Proximity Band

Finding the spatial unit of the right scale for analyzing urban form has always been a challenge for geographers. Administrative divisions often do not match with urban landscapes: each spatial unit is hence heterogeneous in terms of built-up and non-built-up surfaces. The Proximity Band (PB) proposed in Araldi and Fusco (2019) provides a good means of analyzing the urban form from the pedestrian point of view. It is a street-based partition that satisfies, on the one hand, the need to reduce the MAUP (modifiable areal unit problem) by minimizing spatial unit size variability (the size variability of PB partition is lower than that of the administrative unit), on the other, the need for a behaviorally based partition in which both the street point of view and street-network contiguity are incorporated. Finally, the street constitutes the bridging element that enables cross-analysis with different urban morphometric approaches or socio-economic events along the network (distribution of occurrences, movement, perception, etc.), thus avoiding possible spatial unit inconsistencies.

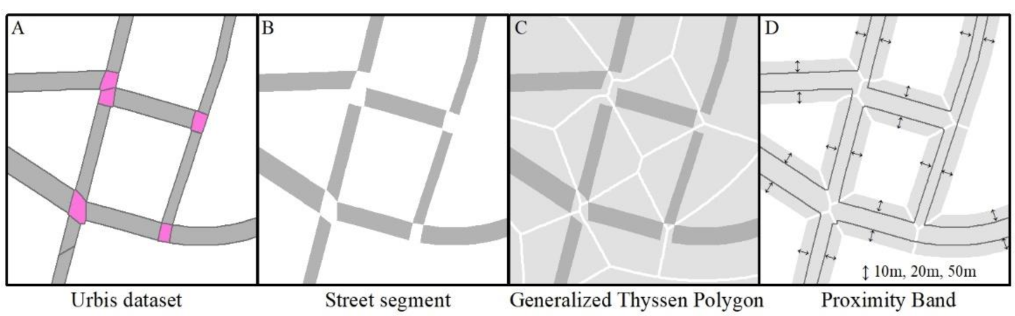

Fig. 2. *Computation of the basic spatial units: from the original data (A) to Proximity Band (D)*

The implementation of the Proximity Band (PB) was adapted to the data available for Brussels (Urbis dataset) [Fig. 2.A]. Street surface data were simplified – notably by removing intersections – to give street segments [Fig. 2.B]. A street segment is the part of a street located between two intersections. Around each street segment, Generalized Thiessen Polygons were defined, allocating to each segment the nearest space [Fig. 2.C]. Then buffers (10 m, 20 m or 50 m) were computed from the street edges [Fig. 2.D]. Three different Proximity Band widths were used, depending on the indicator being considered. Thus 12,457 Proximity bands were identified for the BCR. The longest is 3 km, but 90% of the dataset lies between 20 m and 260 m.

3.2. Computation of urban form indicators using geoprocessing protocols

In the original implementation of MFA, twenty-one indicators were computed for each street segment, each of which described a different morphological aspect of the streetscape. As discussed in Araldi & Fusco (2019), MFA protocol is a flexible procedure which can be easily adapted to each case study by modifying and introducing specific morphometric indicators to capture particular features of the area being studied.

Of the indicators developed in the original MFA applied to the French Riviera, three were not included: (i) *Land ownership fragmentation along the street network* for its high similarity to *Building frequency*, (ii) *Surface slope* and (iii) *Street acclivity,* given the smoother site morphology in Brussels than in the original case study of the French Riviera.

The five indicators called *Prevalence of building types* are based on a classification of the surface of the building footprint adapted to the Brussels case study [Fig. A2, in the Appendix]. Starting from a threshold of 25 sq. m, which allows small structures such as separate garages and garden sheds to be overlooked, we are able to identify: (i) detached or small contiguous houses between 25 and 125 sq. m, mainly found in suburban residential areas and representing the most prevalent building type in Brussels (numerically); (ii) large villas and contiguous houses between 125 and 400 sq. m, encompassing the traditional ‘Brussels townhouses’; (iii) blocks of flats and offices between 400 and 2000 sq. m; (iv) large blocks of commercial, industrial or service buildings 2000–4000 sq. m; and (v) building footprints larger than 4000 sq. m corresponding to large buildings such as factories, railway stations, etc.

Further improvements pertain to the *Local connectivity* indicators, which have been replaced with a combination of two descriptors more suitable for describing the street network layout, while *Dead-end street* assigns a Boolean value to each PBs (similar to Node Degree 1), and a new indicator of *Regular street grid* is implemented as the average angular deviation from the regular street grid with the adjacent streets. This indicator takes the value of 0° if the street forms a right angle (90°) or a flat angle (180°) with all adjacent streets; it takes a value of between 0° and 45° in other cases [Fig. 3].

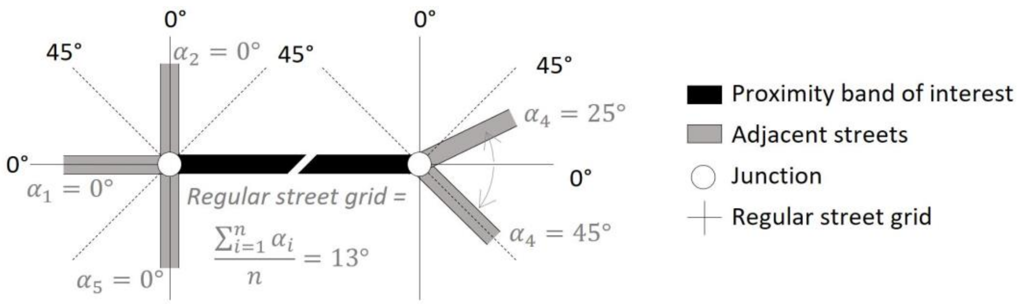

Fig. 3. *Regular street grid indicator: average angular deviation from the regular street grid with the adjacent streets*

The other indicators were implemented as in the original version of MFA (see Araldi & Fusco, 2019 for further details). Each indicator relates to a specific PB depth (10, 20 or 50 meters from the street edge), specified in Tab. 1. We obtained an initial set of 17 indicators classified under three categories: **Street and Street Network Morphology**, **Built-up Morphology**, and **Network-Building Relationship**.

The 17 indicators described so far provide an overview of the urban morphological characteristics of the skeletal streetscape, taking into account only the spatial organization of streets and buildings. As highlighted in the introduction, in order to investigate the importance of vegetation and of available public space, four indicators were specifically designed for Brussels.

The distribution of vegetation in an urban space plays a part in the design and development of urban fabrics. In some urban fabrics, individual trees serve as landmarks or have been added a posteriori. In others, small green spaces have been incorporated into the planning of boulevards and urban fragments. More extensive green features might have been planned for specific urban development. Some neighborhoods, such as garden districts, have fully integrated green space as a major component of their urban design. As we see from these examples, vegetation can take different forms and be located in different positions in relation to the other elements of the urban form. While green spaces are traditionally measured as urban facilities, in this study vegetation is treated as a constitutive element of the urban landscape at the same level as building, plot and street elements. For this purpose, we describe and summarize the various spatial configurations as a combination of three specific indicators, bearing in mind the pedestrian perspective [Fig. 4]. Both private and public green spaces are taken into consideration using the vegetation coverage data of Van de Voorde et al. (2010).

Visible street vegetation coverage quantifies the green spaces directly visible from the street. It can refer to green spaces in the public domain or private front gardens that can be seen by both passers-by and residents. It corresponds to the ratio of the green surface to the total surface of the 10m PBs. *Vegetation coverage* reflects the presence of large green spaces. In our case study, this indicator specifically allows a distinction to be made between the residential fabrics characterizing the eastern and the south-eastern areas of Brussels (as observed in Van de Voorde et al., 2010). Unlike the previous indicator, the vegetation coverage ratio is computed on the basis of the part of the PBs located at more than 10 meters from the street edge. As demonstrated by Asgarzadeh et al. (2012), the presence of trees along the street edge – especially those covering building façades – is an important aspect from the pedestrian's perspective, but not accounted for in the previous indicators. The *Linear density of urban trees* has hence been computed as the average number of trees per meter (point data from the Urbis database). These alignments of trees are not always green enough to be detected by remote sensing, but this indicator allows them to be taken into account.

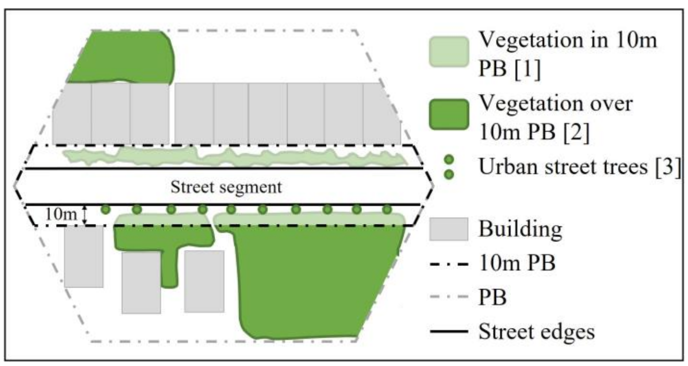

Fig. 4. *Vegetation elements considered for the computation of the three vegetation indicators: Visible street vegetation coverage [1], Vegetation coverage [2] and Linear density of urban trees [3]*

Beyond the vegetation, a further aspect of the urban space considered here is the proportion of the street allocated to pedestrian use. The presence of space devoted to pedestrians is positively correlated with walking (Handy, 2004) and creates meeting places, which provide essential support for social interactions (Gehl, 1987). A *Pedestrian area* indicator is also included in the form of the ratio of pedestrian area to street surface (as in Gil et al., 2012).

In order to investigate the relative importance of these additional indicators of vegetation and pedestrian areas, the MFA procedure will be implemented twice: first we will consider only 17 indicators of built form and street network; the second implementation takes four additional indicators into account. Comparing the results of these two procedures will allow us to understand the relative importance of vegetation and pedestrian space in the definition and identification of the urban fabrics.

Tab. 1. *Definition of the urban form indicators (*see Araldi and Fusco, 2019 for further details)*

Urban fabric component	Name	$S_{ref.}$	Implementation	Output
Street and Street Network Morphology	Street length*	Street surface	Length of the street segment ($L_{str.}$) [m]	$L_{str.}$
	Windingness*		Ratio between Euclidean distance ($L_{eucl.}$) and street length	$1-\left(\frac{L_{eucl.}}{L_{str.}}\right)$
	Regular street grid		Average angular deviation from the regular street grid (α_i) with the adjacent streets (i) [0 to 45°]	$\frac{\sum_{i=1}^{n}\alpha_i}{n}\begin{cases}\alpha \le 45 \rightarrow \alpha_i = \alpha \\ 45 < \alpha \le 90 \rightarrow \alpha_i = 90-\alpha \\ 90 < \alpha \le 135 \rightarrow \alpha_i = \alpha - 90 \\ 135 < \alpha \le 180 \rightarrow \alpha_i = 180-\alpha\end{cases}$
	Dead-end street		Presence of dead-end street [0 or 1]	$\exists\ Deadend\ street$
	Pedestrian area		Ratio between pedestrian area ($S_{ped.}$) and street surf. ($S_{ref.}$)	$\frac{S_{ped.}}{S_{ref.}}$
Built-up Morphology	Prevalence of Building types	50m PB	Ratio between specific building surf. ($S_{\text{x-x m}^2\text{ b.}}$) and total built-up surf. (S_{build}) For: 25–125 sq. m, 125–400 sq. m, 400–2000 sq. m, 2000–4000 sq. m, >4000 sq. m.	$\frac{S_{\text{x-x m}^2\text{ b.}}}{S_{build}}$
	Proximity band coverage ratio*		Ratio between total built-up surf. and PB surf.	$\frac{S_{build}}{S_{ref.}}$
	Building Contiguity*		Weighted average of building fragmentation ($1/N_i$) on attached built-up units (i)	$\frac{\sum_{i=1}^{n}\left(\frac{1}{N_i}S_i\right)}{S_{build}}$
	Specialization of Building Types*		Ratio between specialized building footprint ($S_{\text{sp.b.}}$) and total built-up surf. [%]	$\frac{S_{\text{sp.b.}}}{S_{build}}$
Network-Building Relationship	Building frequency along the street network*	20m PB	Ratio between number of buildings ($N_{\text{b.}}$) and street length [Building/m]	$\frac{N_{\text{b.}}}{L_{str.}}$
	Proximity band building height*		Ratio between building vol. ($V_{b.}$) and PB surf. [m]	$\frac{V_{b.}}{S_{ref.}} = H$
	Open Space Width*		Ratio between open space (S_{nbuilt}) and street length [m]	$\frac{S_{\text{nbuilt}}}{L_{str.}} = W$
	Height/Width Ratio*		Ratio between average building height and average open space width	$\frac{H}{W}$
	Street corridor effect*	10m PB	Ratio between parallel façades ($L_{f.}$) and street length [0–2]	$\frac{L_{f.}}{L_{str.}}$
Vegetation	Linear density of urban trees	10m PB	Ratio between number of trees (N_{tree}) and street length [tree/m]	$\frac{N_{\text{tree}}}{L_{str.}}$
	Visible street vegetation coverage		Ratio between vegetation surface ($S_{\text{veg.}}$) and PB surf.	$\frac{S_{\text{veg.}}}{S_{ref.}}$
	Vegetation coverage	>10m PB		

3.3. Spatial patterns on a network-constrained space

Instead of studying and combining the raw indicators (as traditionally done in Berghauser Pont & Haupt, 2010; Gil et al., 2012; Harvey et al., 2017), the MFA procedure uses geostatistical analysis for the detection of significant spatial patterns for each streetscape morphological descriptor. The local Moran's I (Anselin, 1995) is computed on a network-constrained space (Yamada & Thill, 2010).

Thanks to these network-constrained geostatistical analyses, we pass from a collection of morphological values for each Proximity Band to morphological patterns that correspond to hot and cold spots of given morphological characteristics, using the usual categories of LISA analysis: High-High (HH), Low-Low (LL), and Non-Significant (NS). These geostatistical classifications are the result of analysis of the values of each PB, taking into consideration the local neighborhood connected by the street network, with a topological depth of three units. For further details see Araldi and Fusco (2016), Fusco and Araldi (2017).

3.4. Bayesian clustering approach

The next step consists in studying the spatial co-occurrences of the 21 morphological patterns. The urban fabric seen from the pedestrian point of view is indeed the perception of persistent co-occurrences of given morphological characteristics when exploring urban space. A given urban fabric can be identified by the spatial co-occurrences of every morphological indicator, as well as by a few key characteristics. Clustering approaches aimed at achieving high intra-cluster homogeneity on the basis of variance minimization of the values of all the indicators (such as k-means, SOM and geo-SOM) are not well fitted for this task (Fusco & Perez, 2019). For this reason, Araldi and Fusco (2019) suggest the use of a Bayesian Network clustering of the results of geostatistical analysis to identify urban fabrics. Bayesian Network clustering does not impose cluster homogeneity on all variables (unlike more traditional k-means clustering), deals with categorical variables (such as the outcomes of geostatistical analysis) and allows probabilistic cluster assignment (Fusco & Perez, 2019). These features have proved particularly relevant in the identification of urban fabrics (Araldi & Fusco, 2019).

4. Results and discussion

4.1. The role of vegetation in the identification of the urban fabric

Two clusterings were carried out [Fig. 5]. Clustering 1 includes 17 indicators classified under three categories suggested by Araldi and Fusco (2019): **Street and Street Network Morphology** (except *Pedestrian area*), **Built-up Morphology** and **Network-Building Relationship**. Clustering 2 adds three **Vegetation** indicators and the *Pedestrian area* indicator to the previous set. The two clusterings were carried out using the Naïf Bayesian classifier method as presented by Araldi and Fusco (2019): using different random seeds, 1,000-step random walks explored the solution space to obtain optimal Bayesian clustering of spatial units. The search constraints were a minimum cluster content of 2% of the spatial units, a minimum average probability of assignment of units to each cluster of 0.9 and a maximum of 20 clusters. The optimal number of clusters was determined using a combined score of the log-likelihood of the clustering solution and of its parametric complexity (i.e. the number of clusters). For clustering 1, within eight random-walk searches, an optimum was always found for the 10-cluster solution. For clustering 2, 12 of the 14 random-walk searches showed an optimum for a 12-cluster solution. A successive refining phase of the cluster solution was carried out by imposing this fixed number of clusters on eight new random walk searches. Results were almost identical, the best one showing a contingency table fit score of 58.59% (clustering 1) and 53.41% (clustering 2). The two values are not directly comparable because the numbers of both indicators and clusters are unequal. Clusters are here designated as UFa, UFb,... and UFj in the case of clustering 1 and UF1, UF2,... and UF12 in the case of clustering 2.

The addition of vegetation and pedestrian area indicators (four variables) does not radically change the mutual information that indicators share with the clustering variable when considered individually [Tab. A1, in the Appendix]. **Network-Building relationship** indicators are the most correlated with the clustering variable, as well as *Building Contiguity*, *Proximity band coverage ratio* and *Prevalence of Building type 1 (25–125 sq. m).* Vegetation coverage indicators also have high mutual information with the clustering. The projection of the cluster variables in a space of mutual information shows a gradient of urban intensity [Fig. A3, in the Appendix] that translates on the map as a center-periphery gradient [Fig. 5].

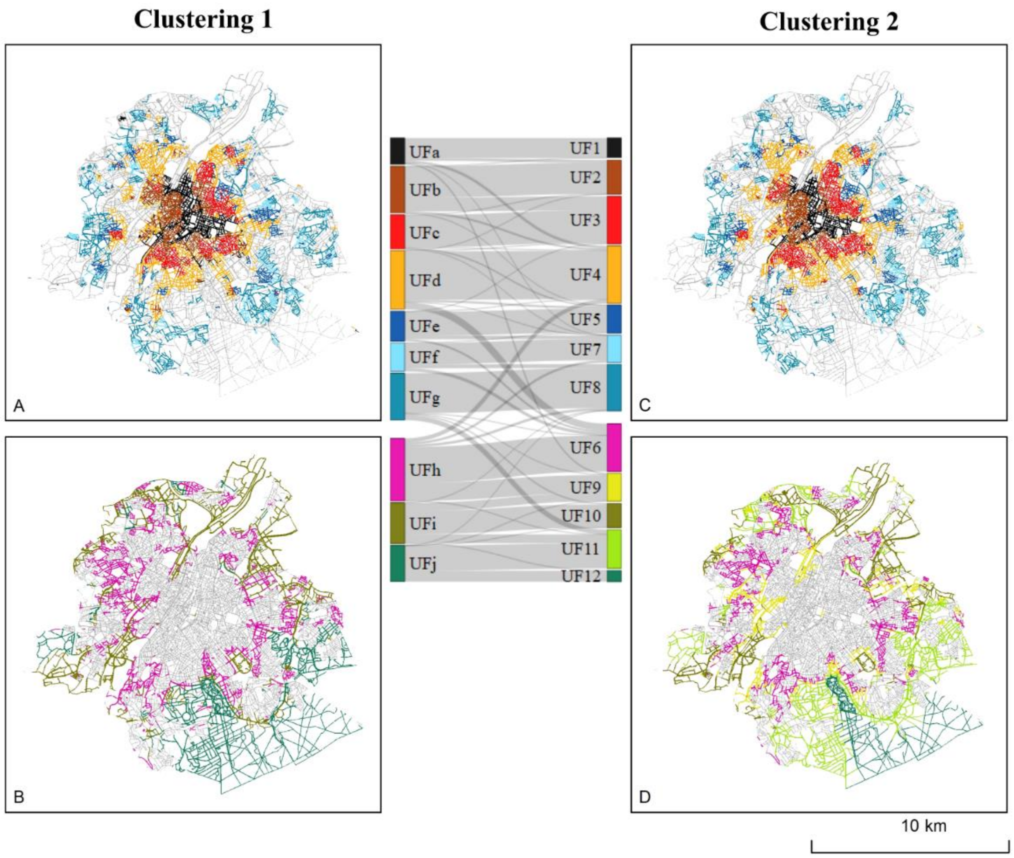

Fig. 5. *Clustering of urban fabrics without (A,B) and with (C,D) the three vegetation indicators and the pedestrian area indicator. The middle graph shows the differences between clusterings 1 and 2. The map splitting highlights the urban fabrics that remain almost unchanged (A to C) and those that change more significantly (B to D).*

The delineation of the urban core as an entity distinct from more peripheral and suburban areas is constant in the two clustering outcomes. However, there is no clear cut-off between these two subspaces: not surprisingly, the urban core has a complex shape, with ramifications following main peripheral axes.

Adding vegetation and pedestrian area indicators allows delineation of meaningful new urban fabrics (UF) in the green suburban area of Brussels. Three clusters (h, i, and j) are redistributed among five new clusters (6, 9, 10, 11, and 12) characterized by a higher average class purity in terms of both the new urban fabrics and the entire clusterization outcomes [Fig. 5.B/D]. UFh – which becomes UF6 – fits better with reality, especially as a large cluster is subdivided into smaller ones. The specialized fabrics found in UFi (and some in UFh) in clustering 1 are split into two clusters in clustering 2: UF9, which takes over the specialized fabrics in a semi-continuous environment, and UF10 in an open environment. The classification of the vegetated suburbs is not accurate in clustering 1. Large green spaces such as forests or parks are not differentiated from green residential neighborhoods. In clustering 2, UFj is divided into two clusters, making it possible to distinguish between natural spaces (UF12) and vegetated suburban spaces (UF11).

The impact of vegetation and pedestrian area indicators is limited as regards the delineation of the central fabrics and the most urbanized periphery. Seven clusters stay almost the same, with a few adjustments: only 17% of variation [Fig. 5.A/C]. They correspond to high-density, well consolidated central areas and planned residential areas in the suburbs.

These observations are consistent with Hermosilla et al. (2014), who demonstrated that the vegetation distribution allows suburban fabrics to be distinguished from the other urban fabrics while, on the other hand, it becomes less efficient for the characterization of compact urban fabrics. In our study, not only do we confirm these results, but we also demonstrate with the implementation of a clustering procedure how the relative spatial configuration arrangement of vegetation and built forms might help characterize different types of suburban fabric.

However, one type of suburban fabric is excepted from this statement: the ‘garden districts’, which are planned residential fabrics typical of Brussels. Three clusters (UFe, UFf, and UFg, which become UF5, UF7, and UF8) are not significantly impacted by the addition of vegetation indicators despite the fact that vegetation abounds in this type of fabric. These fabrics are therefore already well determined by traditional urban form indicators given their specificities in terms of built form and street network.

In view of what has been discussed so far, we might infer the superiority of the second clustering in our case study. From now on we will focus only on clustering 2. There are three main categories of urban fabric: continuous, semi-continuous and open fabrics [Tab. 2]. The sorting of UF clusters is supported by the statistically significant spatial patterns of each indicator for each cluster [see Tab. A2, in the Appendix]. There is a clear vegetation gradient: low value for UF1 to UF4, high value for UF11 and UF12 and intermediate values in between. This gradient of urban intensity is also clearly apparent in the indicators in the category **Network-Building Relationship** and visible (to a lesser degree) in the case of the other two categories.

Tab. 2. *Characterization of urban fabrics in the BCR on the basis of probabilities of morphological patterns (only p(HH)>0,7 and p(LL)>0,7) and interpretation in terms of built-up functionalities. See Tab. A2 (in the Appendix) for detailed results (Picture source: Urbis).*

UF1. Continuous Modern Planned Non-Residential Fabric
- Low vegetation coverage
- Large, tall buildings, absence of narrow buildings
- 'Canyon' effect
→ European Quarter and CBD

UF2. Continuous Traditional Fabric
- Low vegetation coverage
- High regular contiguous buildings
- 'Corridor' and 'Canyon' effect, short, narrow streets
- High building coverage
→ Historical center

UF3. Continuous, Dense Residential Fabric with regular small houses
- Regular and high contiguous buildings
- 'Corridor' and 'Canyon' effect, narrow streets
- Low vegetation coverage and high building coverage
→ Typical Brussels townhouses

UF4. Continuous Residential Fabric with houses and small buildings
- Contiguous buildings
- Low vegetation coverage
- Absence of dead-end streets
→ Typical Brussels townhouses

UF5. Continuous Residential Fabric with regular small houses and wide streets
- Regular narrow adjoining building, no large buildings
- 'Corridor' effect
- Low vegetation coverage in the street
→ Garden neighborhoods

UF6. Semi-continuous Mixed Use/Form Fabric
- Mainly intermediate value (NS) of indicators
→ Intermediate space

200 m

UF7. Semi-continuous Residential Fabric with small houses and small buildings
- Narrow buildings, absence of large buildings
- Presence of vegetation
→ Garden neighborhoods

UF8. Semi-continuous Residential Fabric with houses and average buildings
- Low building coverage
- Wide streets, absence of 'Canyon' effect
- Low-rise isolated buildings
→ Garden neighborhoods

UF9. Semi-continuous Specialized Fabrics
- Absence of narrow buildings
→ Industrial zones

UF10. Open Specialized Fabrics
- Low building coverage
- Long, wide streets, absence of 'Canyon'/'Corridor' effect
- Isolated buildings, absence of narrow buildings
→ Industrial zones and business parks

UF11. Open Suburban Residential Fabric
- High vegetation coverage
- Long, wide streets, absence of 'Canyon'/'Corridor' effect
- Low-rise isolated buildings, low building coverage
→ Villas

UF12. Open Natural and Artificial Non-Urbanized Areas
- Few buildings
- High vegetation coverage
- Presence of pedestrian areas
→ Natural spaces

4.2. On the history of the Brussels urban fabric

Beyond the city's morphology, the resulting typology of urban fabric can be linked to several major developments in the history of urban planning in Brussels. UF2 refers to the medieval fabric, characterized by many small buildings and narrow, winding streets. UF3 and UF4 form the first ring of Brussels. These are dense fabrics characterized by the Brussels townhouses, typical 19th-century bourgeois contiguous houses (Ledent, 2017). The second ring of Brussels is greener, characterized by what could be called 'garden districts' (UF5, UF7, and UF8) and by UF11, fabrics made up of detached houses and villas. Fabrics with a more functional purpose are also highlighted: UF1 contains mainly offices, and the UF9 and UF10 fabrics are mainly industrial areas. See Tab. 2 for more details. In the next sections, two specific points in this history are explored in more detail: the construction of the garden districts (Section 4.2.1) and Brusselization (Section 4.2.2).

4.2.1. Garden Districts

In the inter-war period, the need for social housing became glaringly obvious. Inspired by the English garden cities, several social housing associations were formed to build what can be called 'garden districts'. In Brussels, rather than autonomous cities, it was districts, designed to expand, that were built. These 'garden districts' were conceived by their designers as parts of the city in the countryside, with the underlying idea that the living environment influences the well-being of the inhabitants (Eggericx & Hanosset, 2003). After the Second World War, for financial reasons, the 'garden district' model changed to blocks of flats freely integrated into a park. The aim was to provide modern, comfortable housing made accessible to middle-income households through maximum cost reduction (Leloutre, 2017), following the precepts of the modernist movement.

Many 'garden districts' were built in Brussels. Some were developed with the idea of community in mind, constructed in a spirit of collective management. Other housing estates were inspired by garden cities, without directly appending that name to the urban planning operation or necessarily having any social idea behind them. One of the advantages of the method presented in this paper is that it makes it possible to identify both.

Three clusters of UFs are linked to the 'garden district': UF5, composed of row houses with gardens, UF7, composed mainly of small detached or semi-detached houses surrounded by vegetation, and UF8, composed of larger detached or semi-detached houses surrounded by vegetation. If we take the extent of the 1920s social garden cities (Dessouroux, 2008), 42% of the street segments are in UF7 and 30% in UF8 [Fig. 6].

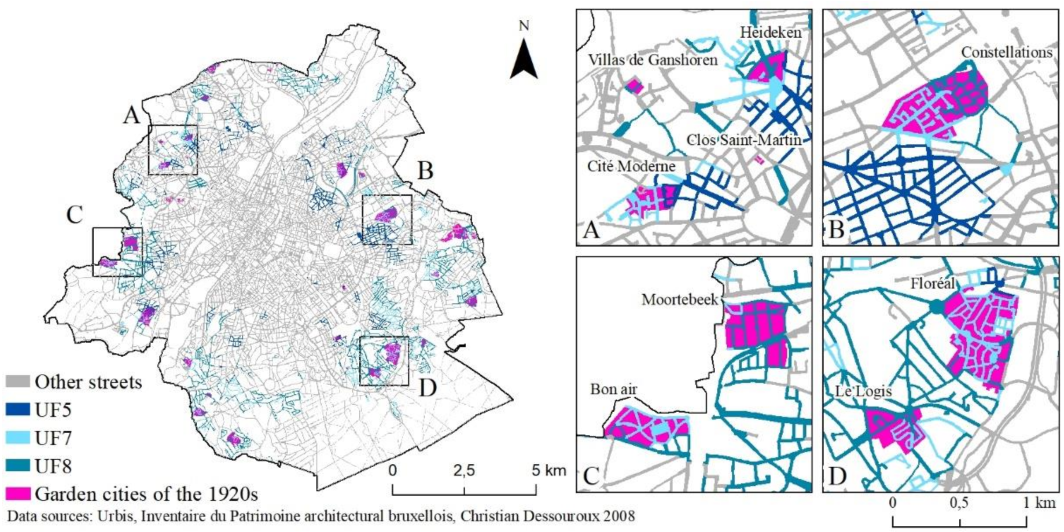

Fig. 6. *UF5, UF7 and UF8 urban fabrics and comparison with the extent of the 1920s garden cities*

4.2.2. Brusselization

Brussels is mainly a tertiary city, with office activities expanded after the Second World War with relatively little regulation. The office towers have shaped Brussels. The financial benefit represented by offices has led to the transformation of some historical fabrics into business districts, to the detriment of residential areas, mixed neighborhoods and the architectural heritage. This phenomenon has been described in the literature as 'Brusselization' (De Beule & Dessouroux, 2011; Dessouroux, 2008).

UF1 includes street segments with high office density [Fig. 7]. These fabrics feature the major business districts of Brussels: the European Quarter, the eastern part of the Pentagon, and the North District.

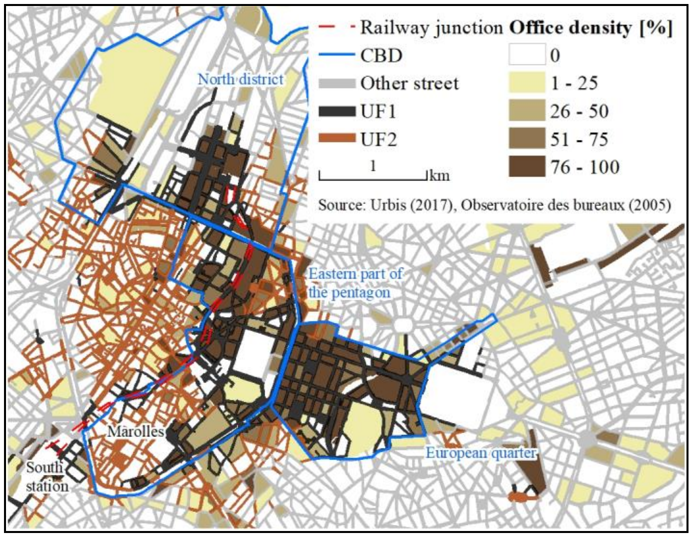

Fig. 7. *UF1 and UF2 urban fabrics and comparison with the extent of the business districts of Brussels (North District, European Quarter and eastern part of the Pentagon).*

The office development in the **eastern part of the Pentagon** [see Fig. 7] has historically been around the Cathedral of Saint Michael and St Gudula, Brussels Park, the small belt (second rampart layout), and the North-South junction. This railway junction shaped the fabric of Brussels because its redevelopment took the form of office buildings, contrasting with the historical fabric. The Leopold District was an upper-class residential district, which gradually became more and more service-oriented. Today, it is more commonly known as the **European Quarter**, because of the European institutions and associated entities (lobby firms, country representations, and embassies). The **North District** is a vast real-estate project that began in the 1960s. Unlike in the European Quarter, the land parcel and the road network have been modified to accommodate high office towers. Implementing this project meant displacing a large part of the neighborhood's population, with an outcome that fell far short of expectations. Following the failure of the North District, a different approach to urban planning was taken. It led in particular to the preservation of the Marolles neighborhood in the face of a project to expand the Palais de Justice (law courts). A few years later, urban planning policy reverted to the earlier approach in the case of office development around the South Station (De Beule & Dessouroux, 2011).

While the method allows converted fabrics to be highlighted, it also identifies, as UF2, historical fabrics that have been preserved, such as the Marolles [Fig. 7]. The typology used sheds light on a heritage that is not always easy to identify – the urban fabric itself.

4.3. Advantages and limitations

Here we aim to compare our results (clustering 2) with the European Urban Atlas (UA) (European Environment Agency, 2012) and with the land use/urban form (LUUF) typology (scenario 3) developed by Vanderhaegen and Canters (2017) [Tab. 3]. This comparison will focus in particular on three aspects: the use of expert knowledge, the objective and the spatial result.

Tab. 3*. Methodological comparison between MFA and two other classifications of urban forms in the BCR.*

	MFA	**Urban Atlas 2012**	**LUUF-typology**
Source	This paper - clustering 2	European Environment Agency (2012)	Vanderhaegen and Canters (2017) - scenario 3
Objectives	Providing a typology of urban street landscapes in Brussels with the further goal of studying human behavior and well-being	Pan-European comparable land use and land cover data for Functional Urban Areas	Mapping types of urban forms and functions for land use mapping (applicable to other cities with similar urban structure)
Basic spatial unit	Proximity Band around street segments	~ Urban block	Urban block
Urban form indicators	• Network and Street Morphology • Built-up Morphology • Network-Building Relationship • Vegetation	• Land uses and percentage of block footprint coverage	• Patch-based: landscape ecological metrics • Profile-based: radial and contour-based profile metrics • Building based: internal structure of the built-up area
Definition of classes	With a neutral prior on classes of urban fabric	18 classes for BCR	Six urban forms defined on the basis of theoretical models
Classification methods	1. Characterization of each indicator in terms of spatial association: clusters of high value, of low value and of non-significant elements 2. Clustering of local patterns using Bayesian approach	Interpretation of high-resolution satellite imagery and use of national in situ data	Classification tree, with tree bagging
Final classification	12 classes	18 classes	6 classes

The UA is essentially based on expert knowledge with little use of automatic workflows. The classes were pre-defined, identical for all Functional Urban Areas. The classification method is also based essentially on expert interpretation of high-resolution satellite imagery and use of national in situ data. Vanderhaegen and Canters (2017) defined, on the basis of the literature, the indicators used to classify the urban blocks. The clustering methodology is a classification tree, with tree bagging of six urban form classes defined on the basis of theoretical models of urban residential morphology. As in the aforementioned work, the indicators used in the MFA method were inspired by the literature. The difference in design is that Bayesian clustering uses a neutral prior for the number and profile of the urban fabric classes (with a maximum of 20 classes). A shared feature of the LUUF and the MFA method is the treatment of uncertainties, also commented on from the perspective of the urban continuum by Vanderhaegen and Canters (2017). Both methods compute to each element a probability of association with the assigned typology. The uncertainties are not addressed in this paper but were discussed in Araldi and Fusco (2019).

The objectives of each typology of urban form of Brussels are also different. The advantage of the UA is that it is a comparable database covering 693 Functional Urban Areas in Europe, which means that the database is not specific to Brussels. The LUUF-typology, even though it applies more specifically to Brussels, has been found to be ‘rather generic […], to be easily applicable to other cities with similar urban structure’ (Vanderhaegen & Canters, 2017, p. 407). The aforementioned authors tested different metrics for the characterization of urban form, and voiced criticisms of the intensive use of landscape ecology metrics. They concluded that specific metrics should be used which describe more explicitly the morphological characteristics of the urban fabric. Their conclusions are consistent with the MFA method. One of the contributions of this paper is to add, and evaluate the advantages of adding, vegetation as an indicator of urban form. The resulting typology of urban street landscapes is specific to Brussels. It provides a detailed overview of the intra-urban fabric of Brussels, and is hence not intended for comparison purposes.

The maps show major differences [Fig. 8]. The UA and LUUF-typology classify each urban block according to its intrinsic characteristics, while the MFA method uses local patterns of street-based urban form indicators. This gives two different results. On the one hand, each urban block is classified while, on the other, the street-based urban fabric is highlighted. So the MFA method does not highlight specific characteristics of each element, but instead provides an overview of the context in which it is found. The choice of method will therefore depend on the objective of the modeling.

In the context of well-being research, the MFA method seems the most appropriate. First, the choice of indicators was made on the basis of the pedestrian's perception of the urban environment, and is consequently human-based. Second, the method highlights urban fabrics (especially through local patterns in the street network) that more closely resemble a pedestrian's experience when walking in the city. Indeed, 'it is by moving from one street to another that pedestrians can experience the spatial variability or homogeneity of urban fabric characteristics' (Araldi & Fusco, 2019, p. 1247).

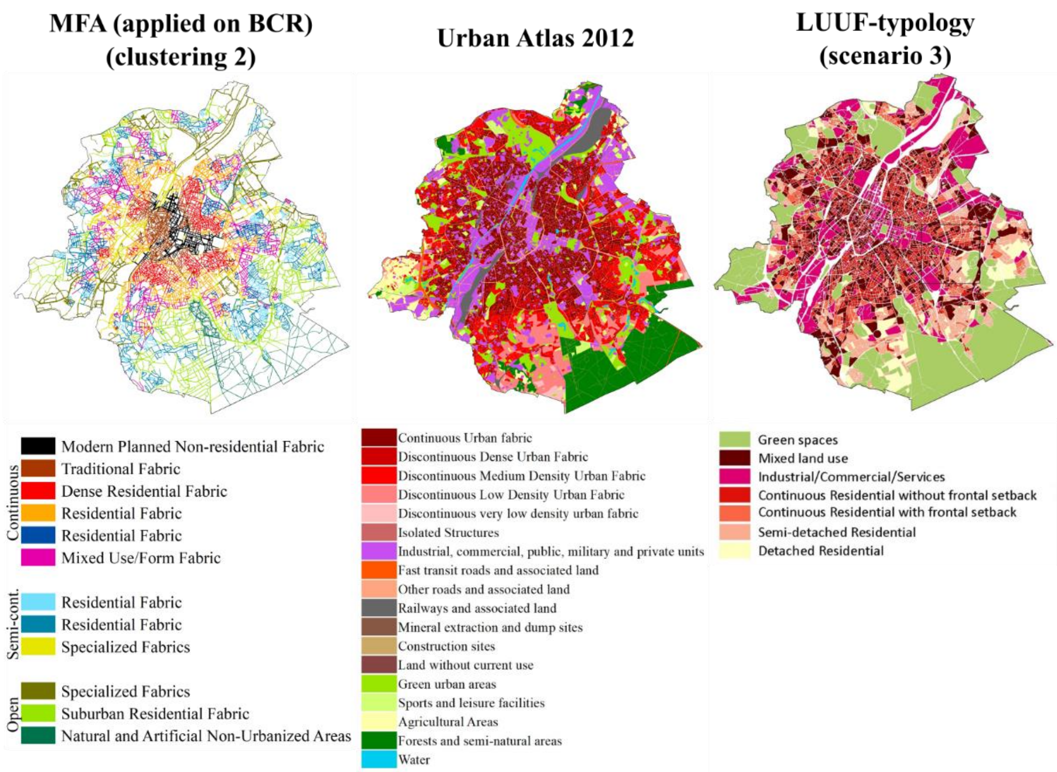

Fig. 8. *Spatial comparison of MFA and two other urban form classifications for the BCR*

5. Conclusions

This paper set out to identify the urban fabrics of Brussel in the same way as the traditional urban typo-morphological approach, but using state-of-the-art geoprocessing protocols. We have chosen two guiding principles: taking a human-perspective approach and adding vegetation to the traditional indicators. In order to achieve this goal, the MFA procedure was adapted and implemented in the specific case study of the BCR. Two classifications were tested. Clustering 1 reflects more closely the original method carried out by Araldi and Fusco (2019). Clustering 2 includes the same indicators, but with the addition of three vegetation-related indicators and one pedestrian-area indicator. The results show that the added indicators allow of a better definition of greener peripheral areas, but that their impact is limited as regards the definition of central fabrics and the planned suburban residential fabric (the ‘garden districts’). The additional indicators allow of a more detailed classification of the urban fabric. Twelve clusters of urban fabrics were identified, divided into three main groups: continuous, semi-continuous and open fabrics. This provides a new way of dividing up Brussels that can be linked to several chapters in the history of Brussels, such as the construction of ‘garden districts’ and Brusselization. The method proved to be successful in identifying Brussels urban fabrics and their spatial arrangements. The typologies identified are consistent with the outcomes of previous studies on the morphological characteristics of the BCR, while developing a more finely grained analysis able to detect urban fabrics from the pedestrian’s point of view. The addition of vegetation indicators has demonstrated the relevance of vegetation in defining the urban fabric, suggesting that it could be usefully included in further studies of the urban form. Vegetation is here seen as an integral part of the urban landscape and measured in terms of its spatial distribution within the streetscape and the urban fabric environment. This protocol differs strongly from the mainstream approach, where vegetation is considered and measured as a distance-based service with accessibility measures.

The resulting typology can be used in various ways in further work as a contextual factor highlighting the variety of urban fabrics in Brussels. Research on human behavior and well-being in the city could benefit from a knowledge of urban forms as perceived by the pedestrian in the street. Discontinuities in the urban fabric could be identified by planners with a view to creating a more cohesive urban street landscape. An objective representation of the urban fabric at any given time could also serve as a reference for future interventions on the form of the physical city. The MFA protocol could even be used to assess the potential impact of specific projects on the urban form.

From the methodological point of view, several aspects could be explored further. For example, a sensitivity assessment of statistical and clustering parameter choices would enable the stability of the MFA protocol to be assessed. Outcomes might also vary depending on the underlying street-network impedances and contiguity modeling approaches that reveal how the urban fabric might be perceived differently, in terms of its walkability properties. Finally, the development of an MFA tool for GIS platforms would also allow the study of the urban fabric to be extended to large synchronic and diachronic comparative studies.

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Appendix

See Fig. A1, Fig. A2, Fig. A3 Tab. A1, and Tab. A2.

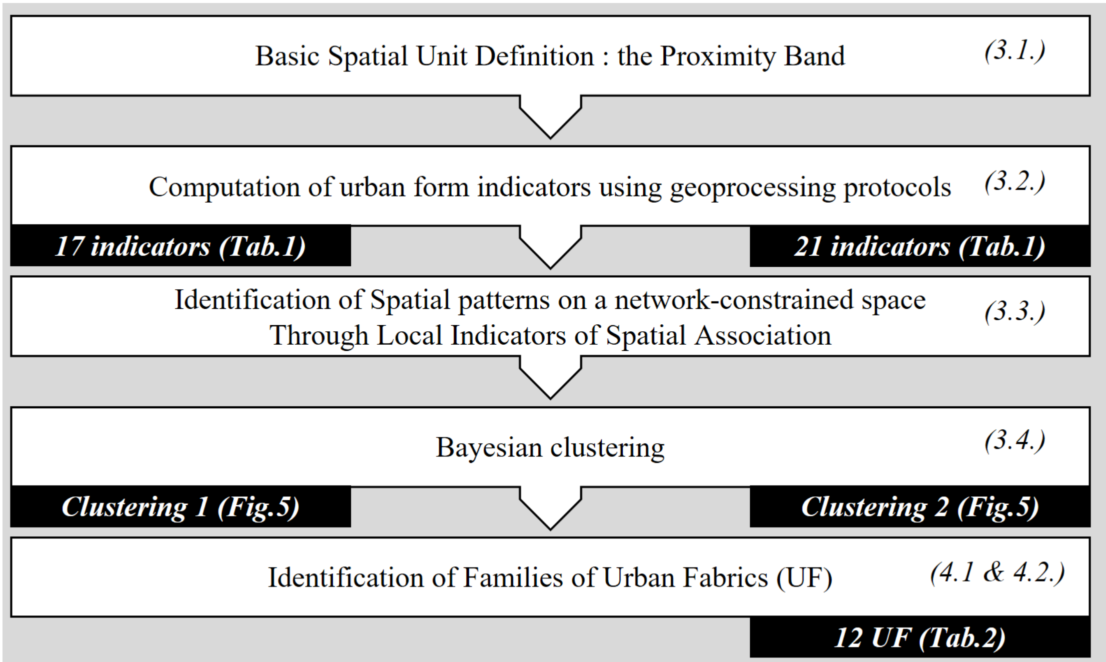

Fig. A1. *Flowchart of the MFA protocol in relation to the corresponding sections in the paper*

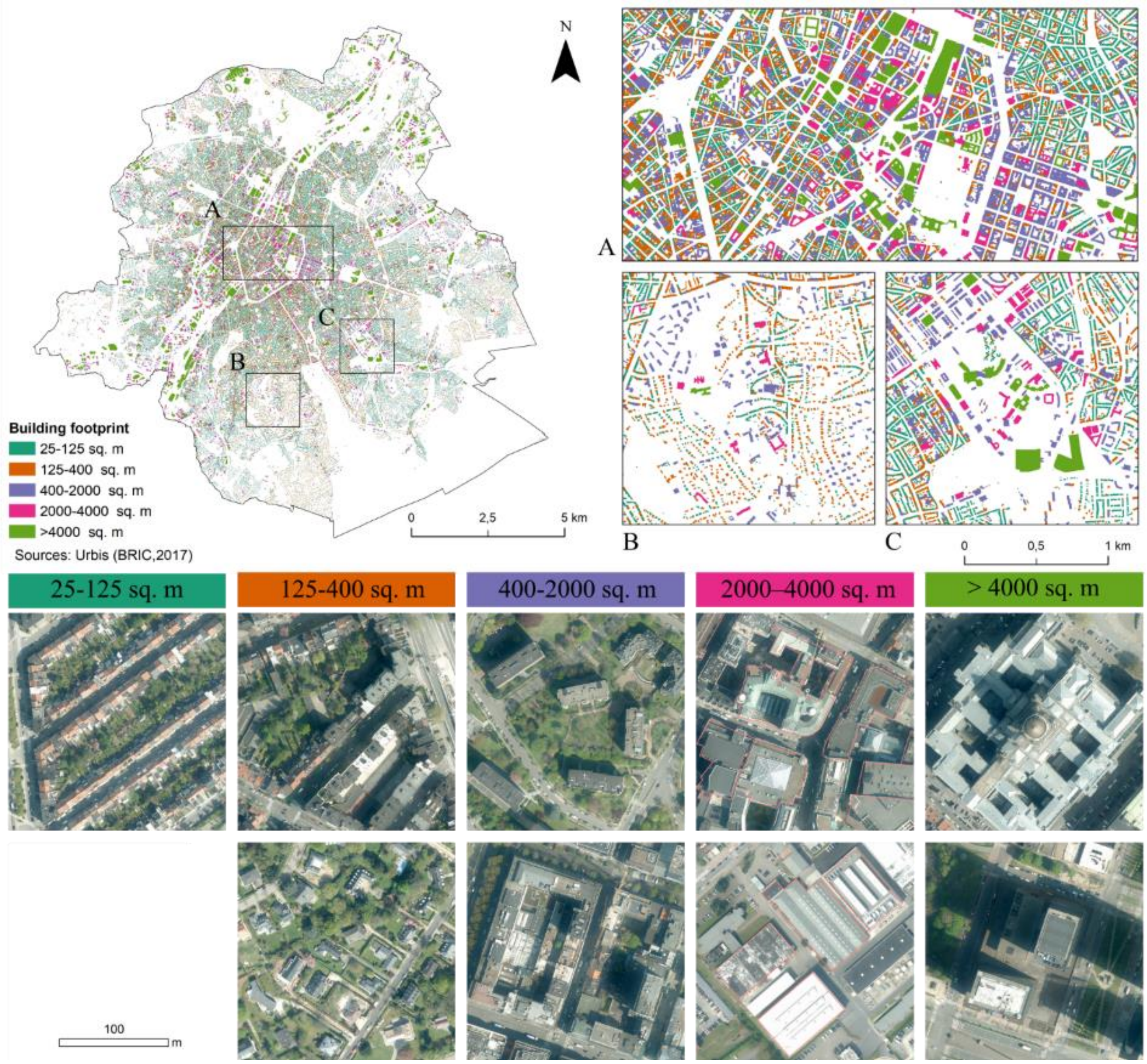

Fig. A2. *Segmentation of building footprints used for the five 'Prevalence of building types' indicators: general map (above) with zooms on three relevant areas (A,B,C) and examples of aerial images for each segmentation (below)*

Tab. A1. *Contribution of each indicator to the clustering definition in terms of mutual information*

Urban fabric component	Name	Clustering 1 Mutual information [%]	Clustering 2 Mutual information [%]
Network Morphology	Street length	16,51	16,41
	Windingness	9,12	8,69
	Grid Perpend.	5,92	5,78
	Dead ends	4,74	4,99
	Pedestrian Area		11,47
Built-up Morphology	Build. (<125 sqm)	24,52	19,92
	Build. (125-400 sqm)	7,68	7,93
	Build. (400-2k sqm)	12,91	12,07
	Build. (2-4k sqm)	8,48	8,34
	Build. (>4k sqm)	8,25	8,45
	Build. Coverage	28,42	27,50
	Build. Contiguity	31,76	30,54
	Build. Specialization	3,92	3,33
Network-Building Relationship	Build. Frequency	28,26	27,47
	Build. Height	36,87	33,61
	Average Width	21,89	20,32
	HW ratio	34,08	31,76
	Corridor Effect	24,64	23,25
Vegetation	Trees		4,21
	Veg. within 10m		24,87
	Veg. over10m		22,47

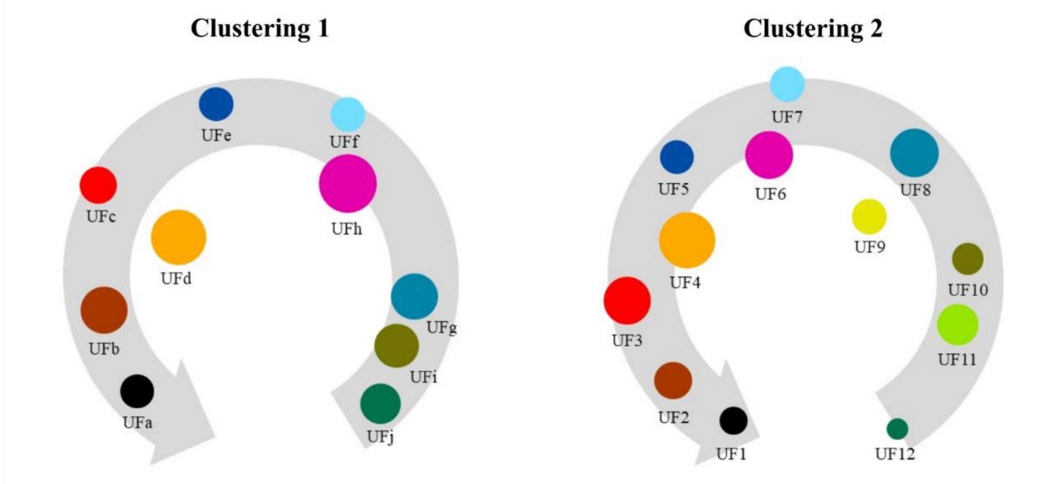

Fig. A3. *Projection of the cluster variables in a space of mutual information for clusterings 1 and 2. Cluster size is proportional to the number of spatial units assigned to each urban fabric (UF). The arrows highlight the presence of an urban intensity gradient: UFa and UF1 are the fabrics of the core areas, while HFj and UF12 are the fabrics mainly covered with vegetation.*

Tab. A2. *Characterizing urban fabrics in the BCR (clustering 2) through probabilities of morphological patterns. If $p(HH)>0,85$ then 'H' is entered in the table, likewise for 'L' and 'NS'. If $0.6<p(HH)<0.85$, then the second category in terms of probability entered as follows: 'H some L' or 'H some NS'. If $p(HH)>0,4$ and $p(LL)>0,4$, then 'H or L' is entered in the table. Similarly for the other combinations.*

	UF1	UF2	UF3	UF4	UF5	UF6	UF7	UF8	UF9	UF10	UF11	UF12
Street length	NS some L	L some NS	NS or L	NS	NS some L	NS	NS or L	NS some H	NS some H	H some NS	H some NS	H
Windingness	NS some L	NS some L	L or NS	NS some L	NS some L	NS some L	NS some H/L	NS or H	NS some H	H or NS	NS or H	NS or H
Grid Perpend.	L some NS	L or NS	NS or L	NS some L	NS some L	NS some L	NS some H/L	NS some H	NS some L	NS some H	NS some	NS or H
Dead ends	L or NS	NS or L	L	L some NS	L some NS	L or NS	Mix	NS some L	NS some L	NS some L/H	NS some L	H or NS
Pedestrian Area	NS	NS or H	NS	NS or L	NS some L	L or NS	NS	NS some L	L or NS	L some NS	L or NS	H
Build. (<125 sq. m)	L	L or NS	H some NS	NS	H	NS some H	H	H or NS	L some NS	L some NS	L or NS	L
Build. (125–400 sq. m)	L or NS	NS some L	NS	NS some H	NS some L	NS some H	L or NS	NS or L	Mix	L some NS	H or NS	L
Build. (400-2k sq. m)	H some NS	NS or H	NS some L	NS	L some NS	NS some L	L some NS	NS or L	H some NS	H some NS	NS some L	L some NS
Build. (2-4k sq. m)	H some NS	Mix	NS some L	NS some L	L or NS	NS some L	L some NS	NS or L	NS or H	NS or H	NS or L	L some NS
Build. (>4k sq. m)	H some NS	Mix	L some NS	NS or L	L some NS	L or NS	L	L some NS	Mix	H or NS	L or NS	L
Build. Coverage	H some NS	H	H some NS	NS	NS	NS some L	NS some L	L	NS some L	L	L	L
Build. Contiguity	NS some H/L	H	H	H some NS	H	NS	NS	L some NS	NS or L	L	L	L
Build. Specialization	H or NS	NS or H	NS	NS some L	NS some L	NS some H	NS or L	NS some L	NS some L/H	NS some L/H	NS some L	L some NS
Build. Frequency	NS some L	H some NS	H	NS some H	H some NS	NS	NS or H	NS	L or NS	L	L	L
Build. Height	H	H	H	H or NS	NS some H	NS	NS some L	L	NS	L	L	L
Average Width	NS or L	L	L	NS or L	NS some L	NS some H	NS some H/L	H some NS	NS or H	H	H	H some NS
HW ratio	H	H	H	NS some H	NS	NS	NS	L some NS	NS some L	L	L	L
Corridor Effect	H or NS	H	H	H some NS	H	NS some H	NS some H/L	NS some L	NS or L	L	L	L
Trees	NS some L	L or NS	NS some L	NS some H	NS or H	NS or H	Mix	NS or H	NS some H	Mix	Mix	L
Veg. within 10m	L	L	L	L	L	NS some L	NS or H	H some NS	Mix	NS or H	H	H
Veg. over10m	L	L	L some NS	L some NS	NS some H	NS some H	H some NS	H some NS	Mix	Mix	H	H