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Comparison of urban fragmentation in European cities – Spatial analysis based on Open Geodata

Ulrich Schumacher and Clemens Deilmann

Abstract

Traffic routes serve to interconnect different locations. At the same time they bisect a spatial area into two “sides” of the route. The paper orientates on the fragmentation effect: Inside urban areas, main traffic routes can segment urban space, whereby physical barriers arise depending on their type (road or rail traffic), width and height (elevated, surface or underground) as well as traffic volume. Functioning as barriers, main traffic routes impair the quality of life in adjacent areas. The focus of this study is not on emissions and pollution but on barrier effects leading to “community severance”. Methodological the principal transferability of the structural analysis of landscape fragmentation to urban space will be shown.

The European Urban Atlas of the Copernicus Land Monitoring Service provides a starting point by providing geodata on land use for almost 700 city-regions (2012). For the purpose of spatial analysis, a polygon geometry of “urban area” is defined and constructed using Urban Atlas data. Classified roads and railway lines are selected from the Open Street Map. Twelve cities with contrasting structures from different countries were selected as case studies. The study proves that the fragmentation of the urban area by main traffic routes can be analysed and measured at a city-wide scale using the indicator effective mesh size. The results provide indication of the spatial cohesion of the urban settlement area, in particular for comparison between cities. For visualization and to better compare cities, the results can be illustrated by calculating a regular grid or network for an average size of unfragmented areas. The effective mesh size describes the degree of fragmentation of urban area and can be regarded as a metric largely independently of city size and density. Such a metric on a city-wide scale can be a supplementary information in the European Union’s Urban Audit.

Urban fragmentation, community severance, spatial analysis, urban metric, effective mesh size, city comparison, Urban Atlas, Open Street Map

Zusammenfassung

Vergleich der urbanen Zerschneidung in europäischen Städten – Räumliche Analyse basierend auf offenen Geodaten

Verkehrswege dienen zur Verbindung verschiedener Standorte. Gleichzeitig teilen sie einen Raum in zwei „Seiten” der Trasse. Der Artikel konzentriert sich auf den Zerschneidungseffekt: Innerhalb urbaner Gebiete können Hauptverkehrstrassen den städtischen Raum segmentieren, wobei sie als physische Barrieren auftreten – abhängig von ihrer Art (Straßen- oder Schienenverkehr), ihrer Breite und Höhe (erhöht, am Boden oder unterirdisch) sowie ihres Verkehrsaufkommens. Hauptverkehrswege können je nach ihrer Barrierewirkung die Lebensqualität in angrenzenden Gebieten beeinträchtigen. Der Schwerpunkt dieser Studie liegt nicht auf Emissionen und Schadstoffbelastung, sondern auf Barriereeffekten im Sinne der „community severance“. Die prinzipielle Übertragbarkeit von Strukturanalysen zur Landschaftszerschneidung auf den urbanen Raum wird gezeigt.

Hier bietet der europäische „Urban Atlas“ des „Copernicus Land Monitoring Service“ einen Ausgangspunkt mit seinen Geodaten zur Landnutzung für fast 700 Stadtregionen (2012). Für die räumliche Analyse wird ein planarer Siedlungskörper definiert und als Polygongeometrie konstruiert – basierend auf Daten des „Urban Atlas“. Klassifizierte Straßen und Eisenbahnstrecken werden aus „Open Street Map“ selektiert. Zwölf Städte mit unterschiedlichen Strukturen aus verschiedenen Ländern wurden als Fallstudien ausgewählt. Die Studie belegt, dass die Zerschneidung des Siedlungskörpers durch Hauptverkehrswege anhand des Indikators effektive Maschenweite im gesamtstädtischen Maßstab analysiert und gemessen werden kann. Die Ergebnisse liefern Einblicke in den räumlichen Zusammenhalt des Siedlungsraumes – insbesondere im Städtevergleich. Zur Visualisierung und zum besseren Vergleich von Städten können die Ergebnisse durch Erzeugung eines regelmäßigen Gitternetzes für eine durchschnittliche Größe von unzerschnittenen Räumen veranschaulicht werden. Die effektive Maschenweite beschreibt den Zerschneidungsgrad des Siedlungskörpers und wird als eine von Stadtgröße und -dichte weitgehend unabhängige Messgröße vorgestellt. Eine solche Metrik auf gesamtstädtischer Ebene wäre eine ergänzende Information für das „Urban Audit“ der Europäischen Union.

Urbane Zerschneidung; community severance; Raumanalyse; urbane Metrik; effektive Maschenweite; Städtevergleich; Urban Atlas; Open Street Map

Introduction

The starting point of fragmentation analysis of urban space is the interrelation between the density of main traffic routes in an urban area and possible impairment of residents' quality of life due to fragmentation (Deilmann et al. 2017, p. 121). Roads and railways serving to interconnect different locations are essential elements in the structural and spatial design of cities. At the same time, however, selected main traffic routes separate or fragment urban structures and can function as barriers. In this way the quality of life can be reduced through the disintegration of urban space. The effects of physical and psychological barriers on the local community are of particular importance (Di Giulio et al. 2008, p. 52). For example, busy roads can fragment local districts and impact social activities between communities on opposing sides of the road. Figure 1 provides a vivid illustration of inner-city fragmentation by a main traffic axis. People tend to maintain contacts and residential services within an area often circumscribed by physical barriers, but contacts cross barriers are difficult and often it is not easy to skip over the barrier.

Kevin Lynch was one of the first to study the urban design and its structure in the image of its inhabitants (Lynch 1960). He differentiated the boundary lines that define an area into natural (e. g. water front or edge of terrain) and anthropogenic ones such as railway lines, elevated roads or through roads. He also saw a problem in the isolating effect and said that boundary lines should ideally be permeable in order not to act as a barrier between areas. In Lynch's work, subjective perception and orientation in the city are the most important aspects. The presented article is primarily concerned with the fragmenting and isolating effect of the anthropogenic boundary lines. Main roads and railway lines are understood as representative elements for barriers from the perspective of humans as pedestrians at city scale – without deepening the perception of boundary lines from the perspective of the inhabitants in the sense of Lynch.

The term "community severance" has been coined to describe this barrier effect. Here we can point to a survey by Anciaes of over 70 international publications (academic studies, reports and official documents) published over the past 50 years (Anciaes 2015). There has been broad discussion of core terms such as "social barrier", "separation" as well as "traffic and people". The following general definition is derived from this survey of relevant publications: "Transport-related community severance is the variable and cumulative negative impact of the presence of transport infrastructure or motorised traffic on the perceptions, behaviour, and wellbeing of people who use the surrounding areas

Fig. 1: Urban fragmentation by a major traffic axis (Schumacher 2015, with friendly permission of the Cath. Parish of St. Mauritius and St. Elisabeth, Halle (Saale))

or need to make trips along or across that infrastructure or traffic" (Anciaes 2015, p. 4). Following this definition, the current study presents an analytical geodata based tool to examine urban fragmentation by main traffic routes on a city wide scale. In particular by drawing comparisons between cities the objective is to raise awareness of this issue – for policy makers – and to initiate more detailed investigations by urban planners.

In his planning principles for the sustainable design of urban traffic at the end of the 20th century, Knoflacher pointed out that the attractiveness of a city depends on its pedestrian permeability and the accessibility of its public spaces (Knoflacher 1997). Yet from the Second World War to recent years, the automobile has dominated the thinking of urban and traffic planners. According to Knoflacher, this has served to restrict the living space of city residents (Knoflacher 1995, p. 27). The barrier effect of traffic routes primarily affects people as pedestrians, who are often neglected in traffic research although they are characterised by high "spatial efficiency" by their autonomous movement, unlimited flexibility in the choice of direction, speed and routes" (Monheim 2010, p. 15–16). It is clear that pedestrian structures in the city are affected by traffic infrastructure, with the level of disruption depending on the density and distribution of routes as well as the volume of traffic. This applies in particular to main roads for car traffic, but also to railway lines within the urban area. Therefore, the focus of the current study is on the structural analysis and determination of the city-specific density of potential barriers, i.e. higher-level road and railway axes, which affect the integrity of the social community in the city as a whole.

Against this background, the spatial analysis investigates the density and distribution of main traffic routes within urban areas (Schumacher and Lehmann 2014). If the degree of fragmentation is high, it can be assumed that the quality of life is impaired for residents of areas affected by community severance. The present study adapts and tests the geometric concept of landscape fragmentation (by assuming spatial complementarity to the urban context) and discusses the results.

In contrast to the numerous studies of landscape fragmentation in open space, few quantitative spatial analyses have been conducted on fragmentation in the urban context. A Spanish study by Sapena and Ruiz (2015) provides an overview of various metrics for urban fragmentation such as area and perimeter, shape, aggregation, diversity and contrast. Based on cadastral data and land use attributes, the authors were able to derive various metrics on the fragmentation of urban districts as aggregated objects, demonstrated using the example of the city of Valencia. Another Spanish study by Ortega et al. (2015) presents a map of urban fragmentation for pedestrians by considering habitat fragmentation on a grid basis (in analogy to a cost function) using the example of a city district in Madrid. The internationally recognised City Biodiversity Index (or Singapore Index on Cities' Biodiversity) provides a total of 23 indicators, whereby Indicator No. 2 serves to measure the connectivity or fragmentation of near-natural areas in the city (Chan et al. 2014). Here the focus is on repercussions for different fauna species. To calculate this indicator (which also considers the impact of barriers), a method is proposed using effective mesh size according to Jaeger (2000). A further ecologically motivated study applied the approach to an investigation of Montreal and Lisbon (Deslauriers et al. 2018). In another study, natural and anthropogenic barriers within the urban landscape were regarded as a network demarcating habitable areas (MacDougall 2011). This was used to derive a taxonomy of first and second order urban barriers. Metrics were determined for the resulting urban spaces, such as the effective mesh size at the level of urban districts, also using the example of Montreal.

The aim of the current study is to undertake a comparative morphological analysis of urban fragmentation from the perspective of humans as pedestrians at city scale. In order to quantify results, we make use of effective mesh size (an established metric in landscape ecology), testing its informative value in the urban area with the aid of open geodata at European level. Such a metric, derived from homogeneous geodata on a city-wide scale, is suitable to supplement the urban statistics of the European Union's Urban Audit. The main objective is the comparison of cities to give orientations on the strength and weaknesses of these cities. With some caution the policy maker could develop guiding principles for the urban planner. Also the results might give the urban planner hints to take a closer view of particularly fragmented urban areas and, if necessary, to link this back to the perception of the citizens.

The authors understand the effective mesh size as one in a series of indicators developed under the topic of spatial metric. Spatial metrics are particularly suitable for quantifying specific physical properties (McGarigal and Marks 1995). These metrics can be traced back mainly to the concept of quantitative landscape ecology (Turner 1989; Uuemaa et al. 2009). Spatial metrics on various topics were investigated and applied in numerous cities worldwide (urban metric) (Thinh et al. 2002; Schwarz 2010; Lowry and Lowry 2014; Reis et al. 2015). The science of urban forms investigates the city as a human habitat (Moudon 1997) and asks how cities can be compared with one another (Deilmann et al. 2017).

Base data

For a structural analysis of cities at the European or global level, it is necessary to use standard geodata for all analysed cities in order to be able to process and evaluate these using a standardised GIS methodology. For this reason, the present study concentrates from the outset on the application of standardised European geodata.

The best-known comprehensive data source for land cover and land use in the European Union is the CLC project "Coordination of Information on the Environment (CORINE) Land Cover". Here satellite images are evaluated in order to derive vector data which could be uniformly classified (a total of 44 classes) at scale 1:100 000. This data is freely provided to all interested users by the European Environment Agency (EEA) for the years 1990, 2000, 2006 and 2012. In the meantime, the CLC data has been integrated into the Copernicus Land Monitoring Service as pan-European geodata. Feranec et al. (2016) give a detailed description of CORINE Land Cover with regard to spatial observation.

The Copernicus Land Monitoring Service offers various global, pan-European and local geodata. This includes the Urban Atlas, which provides detailed vector data on land cover and land use for numerous city-regions in Europe. Such data is available at scale 1:10 000 for 2006 and 2012 with a largely standard nomenclature (max. 28 classes). For the latter reference year, the Urban Atlas has been available since April 2017 for almost 700 European city-regions ("Functional urban areas" or FUA) as Open Geodata (Copernicus Land Monitoring Service 2017). These include all EU cities of more than 100,000 inhabitants as well as their commuting zones; in most cases these are administrative city-regions. The definition of such an FUA can be found in an EU manual (Eurostat 2017, p. 13). As detailed geo-information, this data is used for spatial analysis within the framework of the European Union's Urban Audit (Montero et al. 2014). The Urban Atlas only contains overlap-free geo-objects (polygons) suitable for GIS processing. The data is derived from remote sensing (e. g. SPOT satellite images) and compared with topographical maps. As expected, the focus of land use classification is on urban areas, with no fewer than five density classes defined for the built environment (EU 2016, p. 12ff.). With the help of the Urban Atlas data, generalized patterns of urbanization can be identified by deriving various metrics on settlement structure, as shown in a methodological study that compared Greek cities (Prastacos et al. 2017).

For the analysis of urban fragmentation, data on the main transport network (classified road and rail networks) is required. For a standardised selection of fragmentation-relevant road sections, a Europe-wide comparable category is required, which represents the characteristics of the "Community severance" (such as road width or traffic intensity). Since the segmentation methods from remote sensing concentrate on areal objects such as building blocks (see Blaschke 2010 for an overview), additional vector data with traffic classification are to be used here. For this purpose, linear-shaped geodata from the global project Open Street Map (OSM) is available, which the Geofabrik Karlsruhe offers along with a standard set of attributes. The OSM layer of the road and service road network contains 26 categories according to their

Reference cities for spatial analysis of urban fragmentation

Data source: See map. Data processing and cartography: U. Schumacher, IOER 2018

Fig. 2: Reference cities for spatial analysis of urban fragmentation in Europe

significance for traffic, but no road width information, or traffic volumes (Ramm 2017). Countless users are constantly recording new data and correcting old data for the OSM project, so that the dataset is updated almost daily. This fact must be taken into account when processing OSM data together with geodata captured during a different timeframe. Visual tests for the current example cities assessed the locational fit of OSM data with the Urban Atlas as good. This also seems logical if we remember that OSM data is used to help produce the Urban Atlas (EU 2016, p. 4ff.). Compared to other global data on roads, Open Street Map provides solid base data due to the lengthy period of data collection in most countries (Ibisch et al. 2016). In general, we can say that OSM data is suitable as an additional source of public geodata for the spatial analysis of urban fragmentation.

All geodata used for the analysis is integrated into the uniform geo-reference system "Lambert Azimuthal Equal Area coordinate reference system" (ETRS89-LAEA) as a pan-European standard (INSPIRE 2014).

Reference cities

Twelve cities from different countries were selected for investigation to ensure the widest possible geographical distribution in Europe. Particular emphasis was placed on contrasting urban structures in the selection process. The locations of these reference cities are shown in Figure 2. The cities must fulfil certain conditions in order to ensure meaningful and comparable results under spatial analysis. To this end, the city selection was made according to the following criteria:

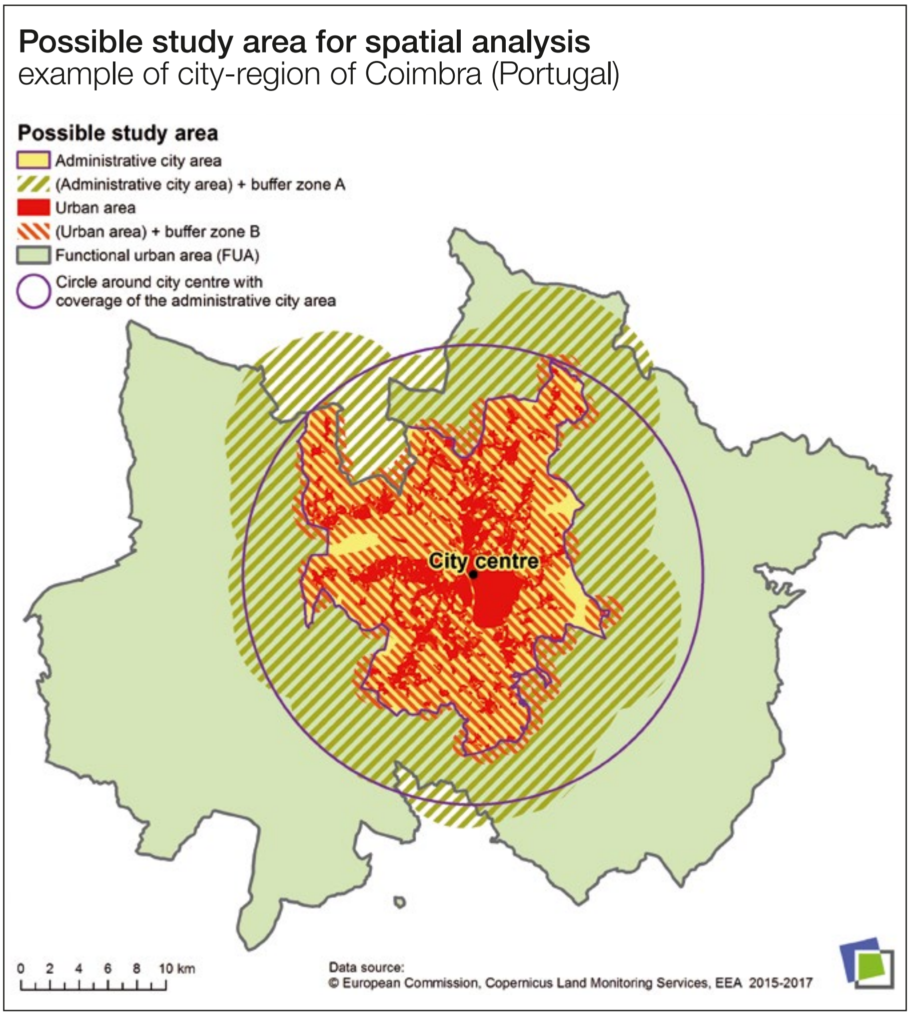
- Large cities of more than 100,000 inhabitants (sufficiently large backdrop of urban area),
- Spatial contiguous administrative city area with no exclaves or islands,
- Urban area easily distinguished from adjacent municipalities.

Of course, a fragmentation analysis can be applied to many more cities and can still be meaningful for any city that does not meet all criteria. But as there exist highly diverse natural and anthropogenic formal structures in Europe, such cases should be preceded by a critical assessment of the applicability of structural analysis.

The study area in the individual cities can be demarcated in various ways. Here the physiognomy of the urban area plays an important role, which will be discussed in more detail in the following section. From a formal geometrical perspective, we note the following feasible options for demarcation (see Figure 3 for one example):

- Administrative city area (core city area),
- Administrative city area + buffer zone A,
- Urban area,
- Urban area + buffer zone B,
- Circle around city centre with coverage of the administrative city area,
- City-region (functional urban area, FUA).

Based on a previous study using German geodata (Deilmann et al. 2017), the comparative analysis of European cities was preceded by an assessment to determine which study area would be both feasible and significant. This assessment revealed certain advantages of the administrative city area, even if these may not always be optimal with regards to structural analysis. The target groups for our city wide analysis are policy makers and urban planners. They are responsible for the overall direction of urban development and give orientation to those in charge of the concrete project planning. Their planning sovereignty finds in the end expression in the infrastructures of transport and water/power supply as well as other structures,



Data source:
© European Commission, Copernicus Land Monitoring Services, EEA 2015-2017

Fig. 3: Possible study area for spatial analysis – example of city-region of Coimbra

and thus in the physiognomy of the urban area. This favours the first option to choose the administrative city area as an area of general decision making on the future urban development.

In addition one could have used the Urban Atlas data for city-regions (FUA). Yet such data pertains to the city's regional boundaries and thus is too widely demarcated from the perspective of the interrelationships with the core city. On the other hand, it is possible that the city boundary in a specific case simultaneously forms the regional boundary. The administrative area of the core city is covered by data from the Urban Atlas in each of the aforementioned options. This is not always the case for the buffer approach. Here the study area (buffer zones A and B or the circle around the city centre) can extend beyond the administrative or FUA area, for example if the core city is located on the regional border and not directly adjacent to further city-regions. This aspect of the geodata supports the argument of restricting the first option. A generalized map of the areas adjacent to the core city enables an assessment of the uniformity of the study area with respect to its isolated location or urban regional environment.

Methodological approach

Design of urban area

Before the fragmentation analysis can proceed, it is necessary to define what we mean by an "urban area". For our analysis, the term "urban area" is used in analogy with the term "Ortslage" from official German spatial surveys. The following definition is given in the documentation of the ATKIS Basic Landscape Model: "An 'Ortslage' is a contiguous built-up area. It encompasses 'residential areas', 'industrial and commercial areas', 'mixed-use areas' and 'areas of special functional character' as well as areas which have a close spatial and functional relationship to these dedicated to transportation, watercourses, areas occupied by 'buildings and other facilities', for recreation, sport and leisure, as well as 'vegetation areas' " (AdV 2015, p. 215).

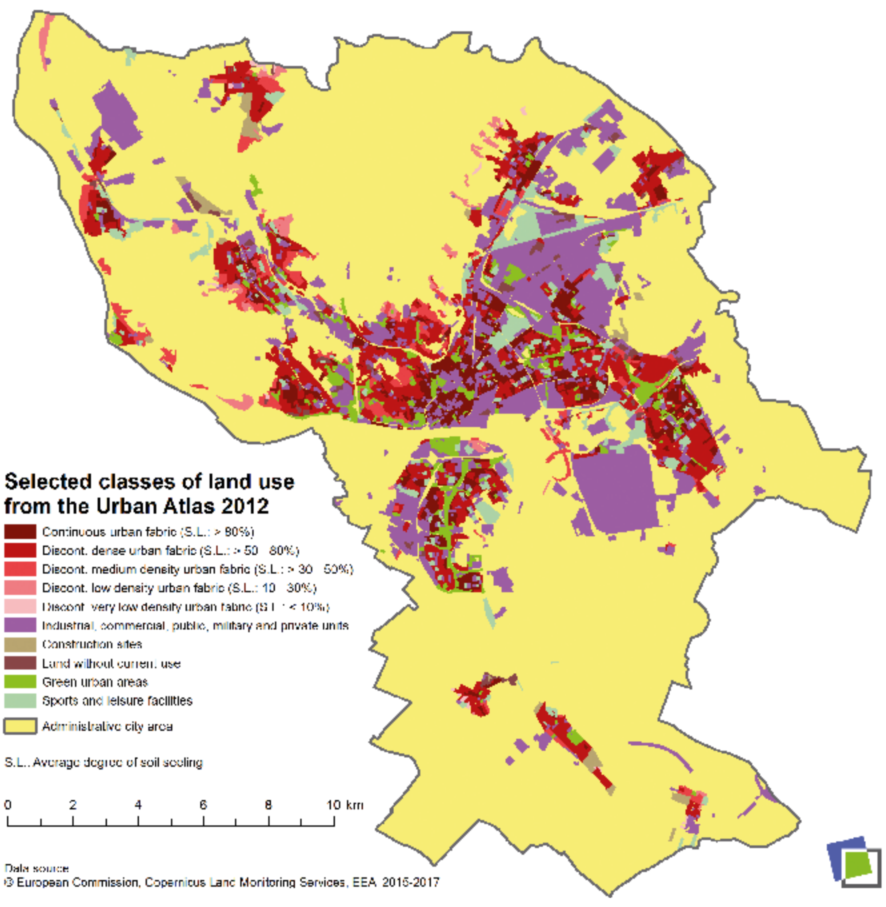
However, the geodata of the Urban Atlas contains no specific layer of "urban area" which could potentially be used for diverse analyses, either within settlements or in open space. Land uses of built-up areas and urban green spaces cannot be merged to an overall urban area, because roads are not mapped as linear elements but as an interconnected spatial area, separating all other land uses block by block.

The first aim, therefore, was to map the basic physiognomic structures (patterns) of the respective city along the above definition in order to reveal the basic polygon geometry of the urban area. Relevant land use classes from the nomenclature of the Urban Atlas (EU 2016) were selected to construct the urban area, i.e. both built-up and green urban areas (see also example in Figure 4). These classes are:

- Continuous and discontinuous urban fabric (built-up area and associated land, residential structures predominant),
- Industrial, commercial, public, military or private units,
- Construction sites and land without current use,
- Green urban areas (public green areas for predominantly recreational use such as gardens, zoos, parks, castle parks and cemeteries),
- Sports and leisure facilities.

Roadways and railway lines have been omitted from the map even though these are actually classified as urban land if located within the urban area. This is because the Urban Atlas contains only two classes of road transport ("Fast transit

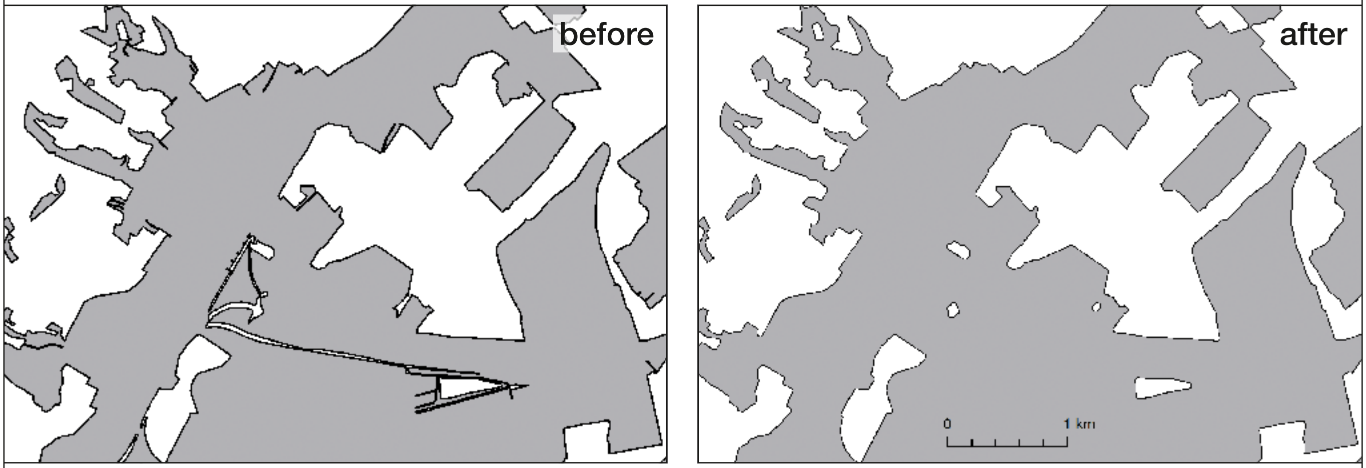
Selected classes of land use from the Urban Atlas mapped for the city area of Bratislava (Slovakia)
(without traffic routes)



Data source: See map. Data processing and cartography: U. Schumacher, IOER 2018

Fig. 4: Selected classes of land use from the Urban Atlas mapped for the city area of Bratislava (without traffic routes)

Generalisation of the urban area by means of double buffering



Source: U. Schumacher, IOER 2018

Fig. 5: Generalisation of the urban area by means of double buffering

roads and associated land", "Other roads and associated land") and one class of railway transport ("Railways and associated land"). The polygonal geo-objects of these transport classes are not distinguished, whether they are within the settlement or in open space. Therefore, these transport areas from the Urban Atlas cannot be used to complete the urban area, because they would spread out like a spider's web into the administrative area.

For further geodata processing, standard methods such as polygon aggregation and buffering were applied and tested with various parameters. This is to be understood as a proposal for the generalization of the urban area – a necessary step to carry out a fragmentation analysis. The gaps in the settlement area arising from the non-integrable transport areas were close by a GIS function to aggregate polygons. Wider gaps could be closed by increasing the aggregation distance. It is the authors' view that a maximum aggregation distance should be set at about 100 m. This value corresponds to the side length of a separate square polygon of minimum size (1 ha) in the urban area (Deilmann et al. 2017, p. 49). To close further gaps within the settlement area, selected classes of more strongly generalized data from CORINE Land Cover (including transport) were used. The integration of parts of both databases was limited as far as possible because of the different scales.

After this processing step, there still remained relatively many small gaps and narrow corridors in the urban area, which could not be closed by further polygon aggregation (the aggregation algorithm recognizes such inner edges as external borders, which must be retained). However, the contours of the urban area could be greatly improved by means of double buffering (first inwards, then with the same buffer distance outwards), as shown by the map section in Figure 5.

The proposed GIS work steps to construct the urban area for one city are summarized in Table 1:

Automated geodata processing is generally to be understood as the first phase of analysis (steps 1–5), which should

Proposed GIS work steps to construct the urban area

Step no.	Explanation of the GIS work steps	Automation
1	Extract the Urban Atlas data for the administrative city area from the city-region (FUA) and select ten relevant land use classes (S.L.: Average degree of soil sealing): • Continuous urban fabric (S.L.: > 80 %) • Discontinuous dense urban fabric (S.L.: > 50 - 80 %) • Discontinuous medium density urban fabric (S.L.: > 30 - 50 %) • Discontinuous low density urban fabric (S.L.: 10 - 30 %) • Discontinuous very low density urban fabric (S.L.: < 10 %) • Industrial, commercial, public, military and private units • Construction sites • Land without current use • Green urban areas • Sports and leisure facilities	Yes
2	Extract the CORINE Land Cover data for the administrative city area and select relevant land use classes	Yes
3	Merge the resulting layers from step 1 and 2	Yes
4	Aggregate the urban area polygons with an aggregation distance of 100 m	Yes
5	Buffer the aggregated polygons outwards and then inwards, each with a buffer distance of 25 m	Yes
6	Edit polygons after comparison with orthophotos for various special cases, e.g. removal of conspicuous elongated structures in open space (motorway construction sites or artificial water basins) which obviously do not belong to the urban area	No

Source: U. Schumacher, IOER 2018

Tab. 1: Proposed GIS work steps to construct the urban area be supplemented by a final stage of interactive processing by humans. In this context, a statement from Germany's Working Committee of the Surveying Authorities is of interest as it acknowledges the limitations of automated geodata processing while promoting human interpretation: "… die Ortslagen-Ausdehnungen werden subjektiv bestimmt und sind weder automationsfreundlich erstellt noch werden die Ausdehnungen automatisiert detektiert …" ("... the spatial extent of settlements are determined subjectively in a step that is neither supported by automated processing nor can be fully automated...") (Kurstedt 2017). Due to the special human ability to recognize complex geometric objects and to distinguish these in a coherent and generalized way, this capacity and competence is needed to finally circumscribe areas for investigation. Such work cannot be simply relegated to an automated process.

Analysis of urban fragmentation

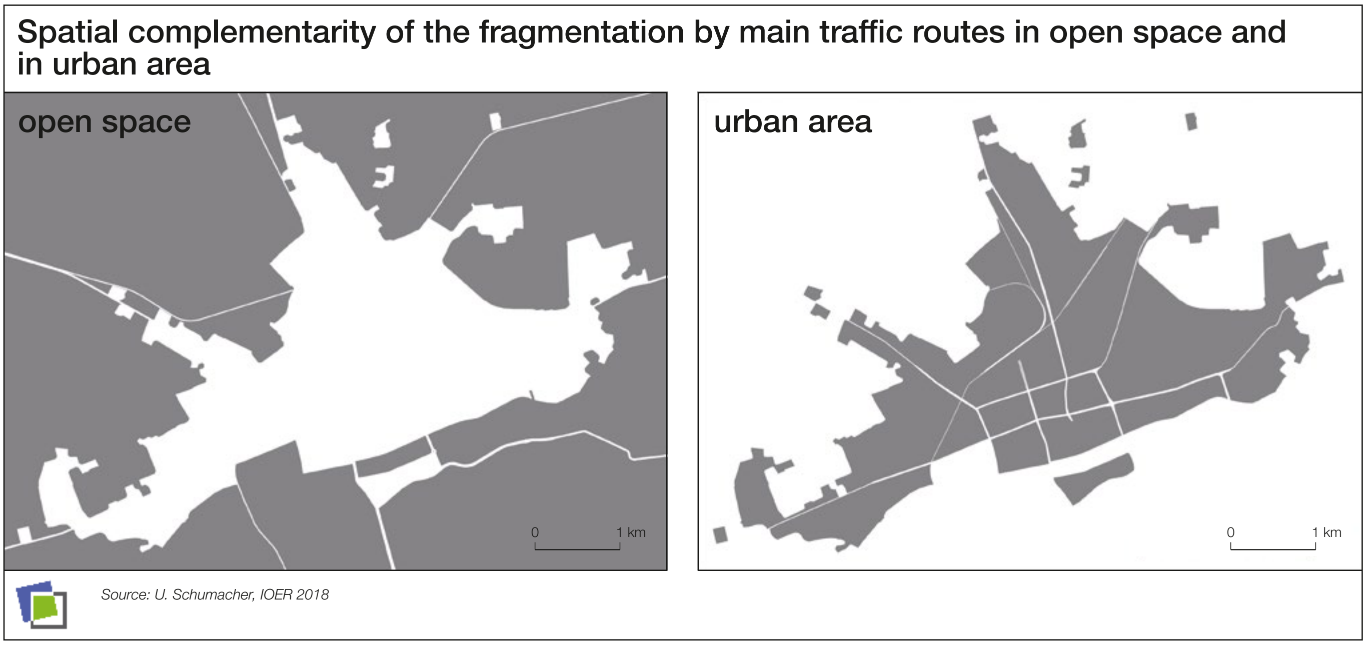
From the perspective of urban morphology, a coherent settlement area is segmented by main roads and railway lines. While these traffic routes serve to connect different locations, they can simultaneously act as barriers. Here we consider those traffic routes in the settlement area that restrict the mobility of pedestrians, i.e. contribute to "community severance". The strength of this barrier effect potentially depends on the type, width and traffic volume of a route section, which generally determines its category. The here introduced analysis which serves as a first rapid assessment, does not include data on traffic densities. This would be one of the next steps to be undertaken by the urban planner. In the current study also other spatial impacts for humans are neglected, specifically noise and pollutants and potential health hazards.

The concept of fragmentation as applied to settlements differs both substantively and in scale from the concept of landscape fragmentation in open space, where the primary focus is on the suitability of habitats for vertebrates or the near-natural potential of landscapes for human recreation (Jaeger 2002; Jaeger et al. 2005; Schumacher and Walz 2000; Walz et al. 2013). Geometrically speaking, the fragmentation of urban space by traffic routes is spatially complementary to the fragmentation of open space (Figure 6). Yet in the case of strong fragmentation, urban space ends up much more like a "group of islands" than is the case with open space, which still usually comprises large contiguous landscapes. This should be taken into account when evaluating metrics.

In the context of landscape fragmentation and the search for suitable forms of representation, the effective mesh size m_{eff} according to Jaeger has established itself as the most important measure of the degree of fragmentation (Jaeger 2000 and 2002; Jaeger et al. 2007; EEA 2011). This measure indicates the mesh size of a theoretically conceived regular mesh. There are good arguments in favour of applying this measure to the quantification of spatially complementary geometries in the urban area. The effective mesh size is an area-proportional additive indicator that offers several advantages, namely clarity due to the absolute area size, comparability of different sized study areas, insensitivity to (separate) splinter areas in the study area as well as a relatively simple calculation. The formula is:

$$m_{eff} = \frac{1}{A_g} \sum_{i=1}^{n} A_i^2$$

A_g = total size of study area
A_1 to A_n = size of patches
n = number of patches
Unit: km^2 Value range: $m_{eff} > 0$



Source: U. Schumacher, IOER 2018

Fig. 6: Spatial complementarity of the fragmentation by main traffic routes in open space and in urban area

The larger the effective mesh size, the lower the level of fragmentation of the settlement or open space by traffic routes (lower strength of the barrier effect). When applying this metric to cities ("urban metrics"), the total extent of the study area A_g corresponds to the urban area. One patch A_i corresponds to a polygon of the fragmented urban area. The sum of all patches gives, maximally, the extent of the urban area of a city. This sum can also be smaller if, for example, the surface area of the fragmentation elements (roads and railway lines) is subtracted.

Additional variables can be derived from the effective mesh size such as effective mesh density or coherence degree (Jaeger 2000 and 2002). The effective mesh density corresponds to the reciprocal value of the effective mesh size. The degree of coherence is calculated by dividing the effective mesh size by the total size of study area. It gives information on the probability that, after fragmentation, two arbitrarily selected points lie in the same patch. Since these formally derived measures have the same information value as the effective mesh size, here we focus on this primary measure of fragmentation.

Roads and railway lines in the urban area must now be selected under the above-mentioned thesis of a strong physical and psychological fragmentation effect. The selection of internationally comparable road categories that fragment the city (motorways, 1st and 2nd order roads or their connections) as well as relevant railway categories (standard gauge) is based on the corresponding categories in Germany. Major tunnels of both modes of transport are not considered relevant to the fragmentation process. They are eliminated from the transport network because in such cases adjacent areas remain connected.

In a modification of the method as described in Deilmann et al. 2017, the fragmentation analysis only considers settlement polygons directly connected to a main traffic route. Isolated island-type settlement polygons without contact to main traffic routes and usually located peripherally in open space are ignored. From the point of view of an urban social-spatial habitat, traffic routes function as fragmentation elements in those instances where they form a barrier between contiguous built-up structures and where they reduce the quality of life in adjacent areas. In the formula of the effective mesh size, only the first-mentioned settlement polygons (with contact to main traffic routes) and their respective sub-areas A_i are summed.

GIS work steps to construct the urban fragmentation geometry

Step no.	Explanation of the GIS work steps
1	Preparation of geodata from OpenStreetMap (Ramm 2017): Data extracted from the OSM road and railway network for the administrative city area
2	Selection of the main road network (motorways, trunks, 1st and 2nd order roads or their connections), except tunnel sections > 100 m
3	Selection of the railway network (standard gauge only; no narrow gauge railways, no trams, etc.), except tunnel sections > 100 m
4	Buffering of the selected transport networks: • Roads: total standard buffer per carriageway of 10 m • Railway lines: total standard buffer per line of 6 m
5	Merging the buffered main road and rail network to form a planar main transport network
6	Erasing the planar main transport network from the urban area
7	Spatial joining of the fragmented urban area with the main transport network: Marking of urban polygons that run tangentially to the main transport network
8	Deletion of urban area polygons not tangential to the main transport network

Source: U. Schumacher, IOER 2018

Tab. 2: GIS work steps to construct the urban fragmentation geometry

Numerous small patches are created in the fragmentation geometry at motorway intersections, green strips between separate lanes, roundabouts and between the tracks at railway stations. Dead-end railway tracks also form incisions in the surrounding areas. The effective mesh size is generally rather insensitive to such effects due to the algorithms defined by Jaeger (Jaeger 2002, p. 167 and p. 159). This was also confirmed by exemplary tests within the scope of our own investigations. Therefore, the fragmentation geometry does not require further modifications.

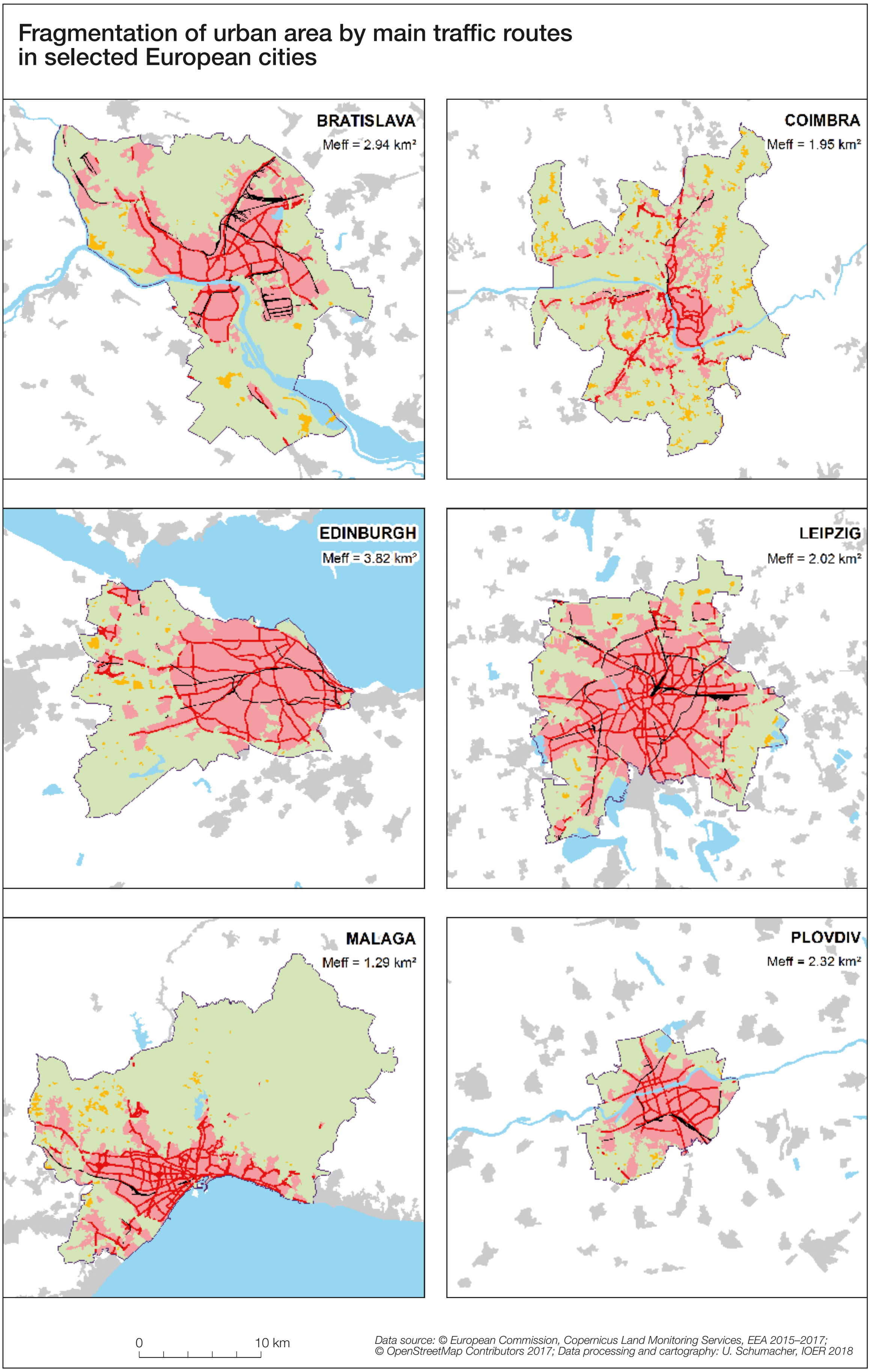
As already explained, selected geodata on road and rail traffic from Open Street Map was used to supplement the Urban Atlas data in order to construct the urban fragmentation geometry. This resulted in the following GIS processing steps each for a city (Table 2):

This provides an urban fragmentation geometry of the main road and rail transport network in the urban area of the entire city for analysis and evaluation.

Results – comparative analysis

The main objective is the analysis of urban fragmentation in a city-wide comparison. The maps of reference cities give a visual overview (Figure 7). The colour of the polygons in the urban area indicates whether they are tangential to the main transport network (light red) or not (ochre). Water bodies (marine and inland waters) are shown in generalized form in blue (from CORINE Land Cover). Settlement areas located outside the administrative city boundary are indicated in generalized form in gray (from CORINE Land Cover) to provide some orientation. It should be noted that basic topographic data could be added for more details in a larger scale.

The larger the effective mesh size of unfragmented settlement areas in a city, the better the potential quality of life for citizens in terms of lower community severance (smaller potential barrier effect). Larger mesh sizes occur when road traffic is bundled or is located towards the edge of the urban area, without any variation in the total length of the main road network. On the other hand, a small effective mesh size means that the urban



Data source: © European Commission, Copernicus Land Monitoring Services, EEA 2015–2017; © OpenStreetMap Contributors 2017; Data processing and cartography: U. Schumacher, IOER 2018

Fig. 7: Fragmentation of urban area by main traffic routes in selected European cities

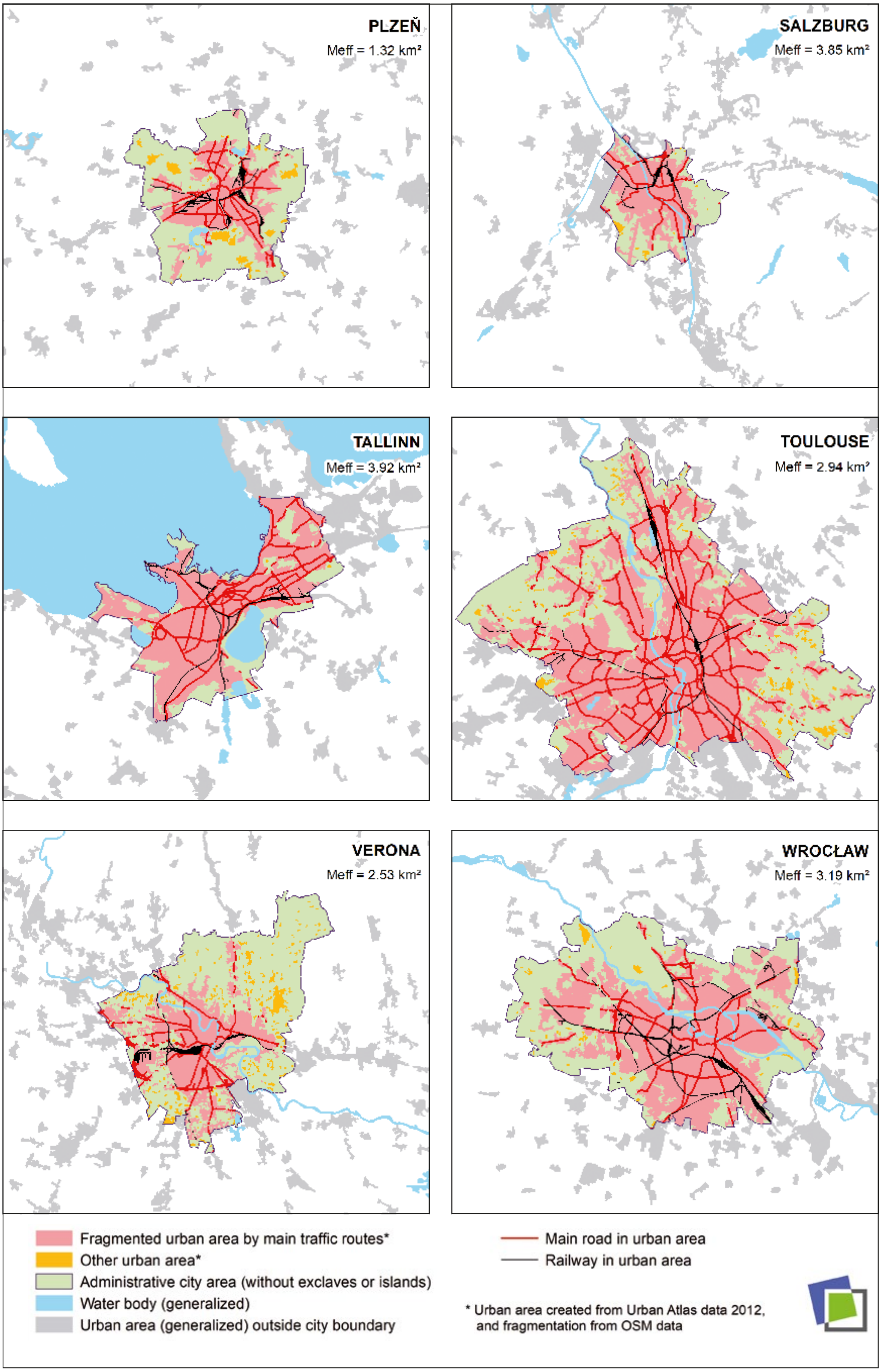
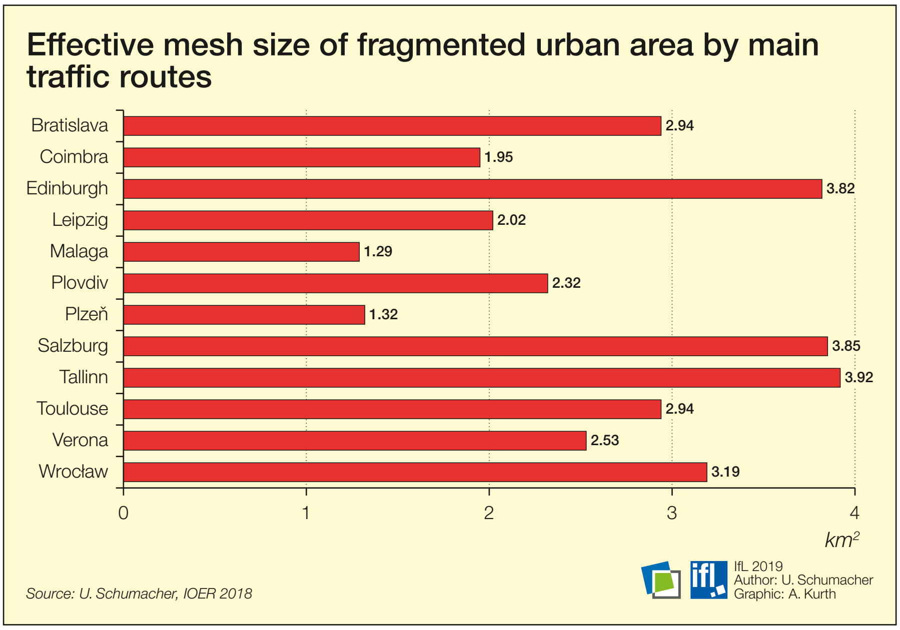


Fig. 7: Fragmentation of urban area by main traffic routes in selected European cities



Source: U. Schumacher, IOER 2018

Fig. 8: Effective mesh size of fragmented urban area by main traffic routes in selected European cities

area is heavily fragmented by main traffic routes, with corresponding physical and psychological barrier effects. A bar graph provides a clear overview of these values for the selected cities (Figure 8).

As explained above, the effective mesh size according to Jaeger is used to evaluate urban fragmentation. The results show a disparity in value between the example cities up to a factor of 3. The smallest values are indicated for the cities of Malaga (1.29 km^2) and Plzen (1.32 km^2) while the largest effective mesh sizes are indicated for the cities of Tallinn (3.92 km^2), Salzburg (3.85 km^2) and Edinburgh (3.82 km^2). Such differences in value should stimulate further investigations to determine which urban characteristics (topographic, physical or historic) are responsible. Clearly, further research and further indicators are required to enrich the understanding of fragmentation. The following discussion can only deliver some preliminary interpretations and can point to interesting further questions for research.

Located on the southern coast of Spain, Malaga has a highly fractured urban area (due to its dense historical centre and sprawling suburbs) further fragmented by main traffic routes. The local topography (especially the relief in the northeast of the city area) strongly affects the development of settlement areas, particularly those located in narrow coastal strip beside the Mediterranean. For this reason, traffic routes have to be bundled. Numerous road and railway tunnels cause a certain reduction of fragmentation in the urban area. In addition, dense building structures in Malaga (as in other southern European cities) play an important role in protecting against summer heat.

The relatively small mesh size calculated for the urban area of the Czech industrial town of Plzen can be explained by the dense and evenly distributed main road network combined with a comparatively dense railway network. Here we particularly note the largely well-preserved traditional urban structures.

The city centre in the Estonian capital of Tallinn is densely developed, in contrast to most of the suburbs. There are no physical barriers to urban expansion in the periphery; only the Baltic Sea and larger lakes form natural barriers. Tallinn grew into a large city during the Soviet era when extensive urban development was pursued through the construction of large-scale housing estates and an extensive transport network. Therefore, the meshes of the main road network are relatively large throughout the entire urban area.

Salzburg in Austria has a relatively compact urban area, with bundling of the main road network and large traffic-calmed zones. The railway network is also highly concentrated. Some of the railway lines run parallel to main roads, thereby reducing the fragmentation effect.

In the Scottish capital Edinburgh, we see a fairly uniform distribution of the main transport network. The effective mesh size is large because of the presence of extensive and unfragmented parks (including golf courses) often spatially linked to built-up areas. This settlement pattern is typical of the UK.

The basic indicators are given in Table 3. The populations of the investigated European cities lie between 143,000 (Coimbra) and 631,000 (Wroclaw). The administrative areas range from 66 km^2 (Salzburg) to 461 km^2 (Toulouse); these two cities also have the smallest and largest urban areas. The ratio of the urban area to the city area in Malaga and Coimbra is just under 22 %, while in Tallinn it is more than 70 %. The number of separate polygons of the urban area (without fragmentation analysis) is not simply dependent on the size of the city: Tallinn has only seven polygons each, while in contrast, Verona has the highest number of polygons at 222, reflecting the strong urban sprawl in the Italian province of Veneto. The mean size of separate polygons of the urban area also differs greatly between cities, with very small values in Verona and Coimbra and a clear maximum in Tallinn. The final indicator, namely settlement density, shows marked differences between the example cities, ranging from 2,0 inhabitants per km^2 in Coimbra to 6,6 inhabitants per km^2 in Malaga.

Bivariate correlation analyses indicate no or only weak correlations between the effective mesh size of parts of the urban area fragmented by main traffic routes and the other indicators given in Table 3. While no correlation can be determined to the size of the city, a weak positive correlation is found to the ratio of urban area to administrative city area and also to the mean size of polygons of the urban area. Such correlations are expected because bigger polygons of the urban area can potentially

Population and basic shape characteristics of selected European cities

City		Population (rounded) *[thousand]*	Admin. city area (calc. by GIS) *[km²]*	Urban area					Settlement density (Number of inhabitants per urban area) *[1/km²]*
				Absolute *[km²]*	Ratio to admin. city area *[%]*	Number of separate polygons	Mean size of polygons *[km²]*	Eff. mesh size, dissected by main traffic routes *[km²]*	
Bratislava	SK	413	367.55	121.89	33.16	56	2.18	2.94	3,388
Coimbra	PT	143	319.44	70.18	21.97	188	0.37	1.95	2,038
Edinburgh	GB	493	263.40	129.86	49.30	65	2.00	3.82	3,796
Leipzig	DE	510	297.98	170.51	57.22	57	2.99	2.02	2,991
Malaga	ES	567	394.34	85.73	21.74	89	0.96	1.29	6,614
Plovdiv	BG	338	101.89	53.05	52.07	37	1.43	2.32	6,371
Plzeň	CZ	167	137.68	53.72	39.02	45	1.19	1.32	3,109
Salzburg	AT	149	65.64	39.33	59.92	16	2.46	3.85	3,788
Tallinn	EE	402	156.41	110.50	70.65	7	15.79	3.92	3,638
Toulouse	FR	725	461.21	272.88	59.17	190	1.44	2.94	2,657
Verona	IT	255	198.99	72.74	36.55	222	0.33	2.53	3,506
Wrocław	PL	631	292.79	159.58	54.50	58	2.75	3.19	3,954

Sources: U. Schumacher, IOER 2018; Population from Eurostat, Urban Audit 2012

Tab. 3: Population and basic shape characteristics of selected European cities

contain larger unfragmented subareas. Nevertheless, the above values for effective mesh size point to the relative independence of this index and recommend it as a meaningful indicator of urban morphology. The authors consider the exemplary analysis along 12 cities (based on the city selection criteria described above) as sufficient to recommend the effective mesh size as an useful informative indicator in the urban context. Further empirical studies should be carried out to enhance this thesis.

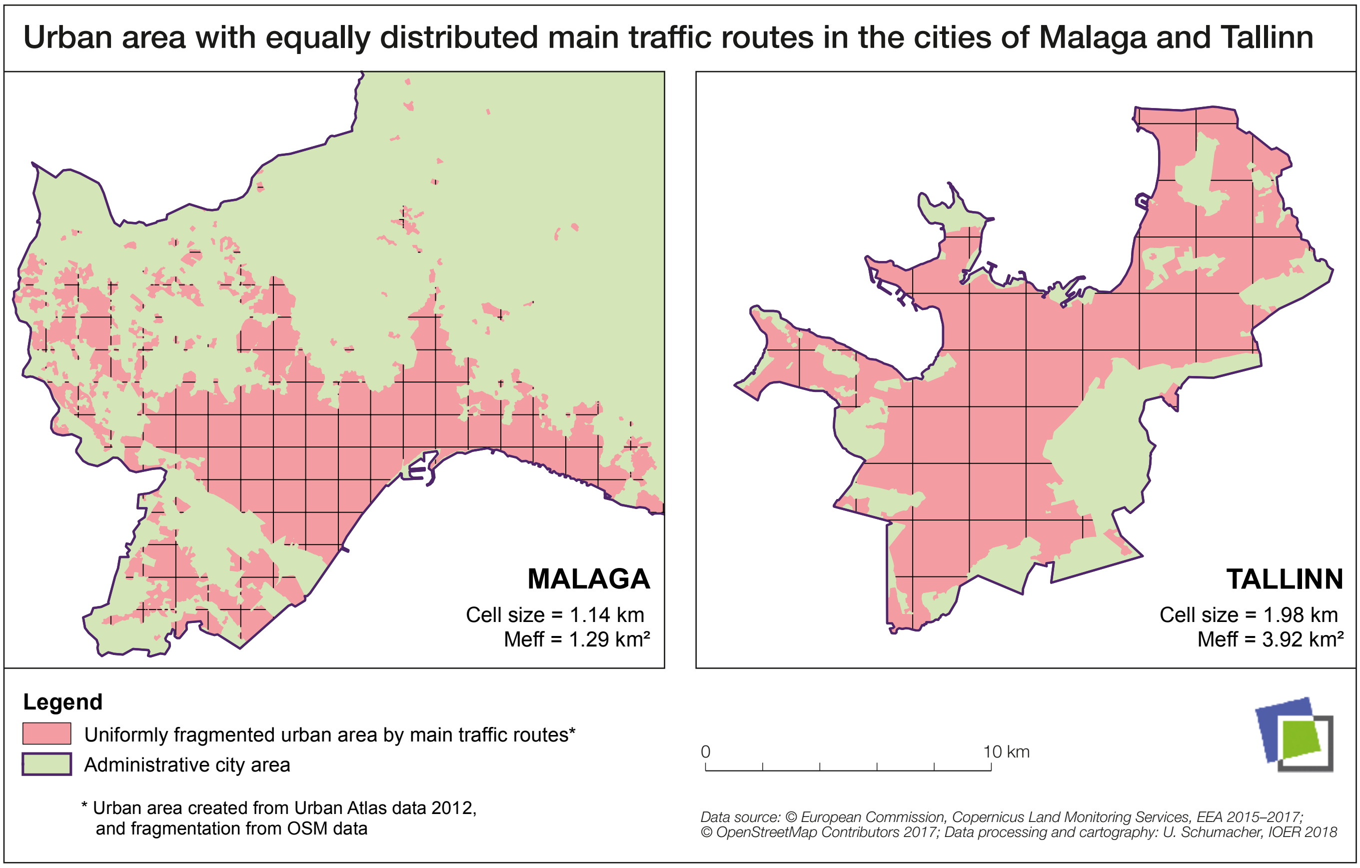
To visualize the degree of urban fragmentation – in analogy to the landscape fragmentation of regions (see the example given in Jaeger et al. 2007, Fig. F10) – the indicator can be mapped by constructing a regular grid or network overlaid onto the urban area of a city. The edge length or cell size of this network is derived from the square root of the effective mesh size, calculated for the urban area fragmented by main traffic routes. This corresponds to a theoretical concept of urban structures on a city-wide scale. The denser the network, the more pronounced the fragmentation of the urban area. This is particularly clear if we compare the extreme values of the selected European cities (Figure 9): The city of Malaga shows the most intense urban fragmentation (smallest cell size: 1.14 km) while the urban area of Tallinn is the least fragmented (largest cell size: 1.98 km). The two extreme values also confirm that the coastal location of cities plays no role in the degree of urban fragmentation.

Conclusions

The paper demonstrates the applicability of an approach developed within ecological landscape analysis to measure landscape fragmentation for analysing the extent of fragmentation of urban areas by main transport networks

In geometric analogy to landscape fragmentation, the degree of fragmentation of the urban area by main roads and railway lines can be quantified by means of the effective mesh size (according to Jaeger). The robustness of this index to isolated urban splinters was confirmed by exemplary tests. The sensitivity of the index to large areas requires consistent geodata, especially concerning the fragmentation geometry. In principle, this study supports the following thesis: The effective mesh size can be regarded as an independent and suitable indicator to assess the extent of (un)fragmented settlement areas in a city. It can be easily visualized by overlaying a regular network with corresponding cell size onto the mapped urban area. This is a useful contribution to the spatial analysis of community severance. The findings can stimulate further research to better understand differences between European cities. Urban researchers and urban planners can obtain insights into the strengths and weaknesses of urban physiognomies when comparing cities. The results of urban structural analysis can give overall orientation on the city as a whole and strategic development targets, but no advice for concrete projects.

A further study result is the proposed method – using the example of urban fragmentation – to create a planar urban area using open geodata at the European level. Unfortunately, the Urban Atlas does not include a layer in the sense of a planar urban area analogous to the German ATKIS feature type “Ortslage”. This drawback affects not only the fragmentation analysis but also potentially other GIS-supported analyses within settlements as well as in open space. It would be advantageous to have a layer “urban area” as part of the Copernicus Land Monitoring Service as basis for certain GIS-analysis.



* Urban area created from Urban Atlas data 2012, and fragmentation from OSM data

Data source: © European Commission, Copernicus Land Monitoring Services, EEA 2015–2017; © OpenStreetMap Contributors 2017; Data processing and cartography: U. Schumacher, IOER 2018

Fig. 9: Urban area with equally distributed main traffic routes in the cities of Malaga and Tallinn

The selection of international categories of roads and railway lines potentially relevant to urban fragmentation is possible and consistent according to the Open Street Map. There is a good geometric fit between the OSM data and the Urban Atlas data. A random visual comparison with aerial photos and other reference data revealed only a few gaps in the road network, which could be closed by interactive editing. In several cases, discontinued railway lines are still included in the OSM data. The OSM data supplied by Geofabrik Karlsruhe is from 2017. Retrospective data on road or rail networks with a closer temporal fit to the Urban Atlas 2012 were not available for analysis, because OSM are only provided up to date. Any resulting inconsistencies must be taken into account in a detailed interpretation.

Further research is needed to better demarcate the urban study area in order to ensure the general applicability of the presented analysis approach of urban fragmentation, especially in the case of agglomerations. In addition, possible relationships between urban fragmentation on the one hand and relief, climate zones, natural vegetation as well as country-specific settlement structures and cultural influences are further interesting research questions. Results might lead to a deeper understanding of fragmentation and cause-effect relationships. There is little doubt that sections of subordinated roadways can also cause similar barrier effects to pedestrians as the main traffic routes considered here. Detailed analyses of the impact of such roadways are needed. Such investigations, however, should be carried out at larger scales for specific districts and differentiate between various classes of barriers.

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Резюме

Ульрих Шумахер и Клеменс Дейлманн

Сравнение фрагментации европейских городов — пространственный анализ на основе открытых геоданных

Маршруты движения используются для соединения разных мест. В то же время они делят пространство на две «стороны» маршрута. Данная статья посвящена этому эффекту фрагментации: в городских районах основные дороги могут делить пространство на сегменты, выступая в качестве физических барьеров в зависимости от их типа (автомобильный или железнодорожный), ширины и высоты (надземный, на земле или под землей) и интенсивности движения. Главные транспортные магистрали могут значительно ухудшать качество жизни в прилегающих районах в зависимости от своего разграничивающего действия. Основное внимание в данном исследовании уделяется не выбросам и загрязнению, а барьерным эффектам с точки зрения «разделения сообщества». В нем показана принципиальная переносимость структурного анализа фрагментации ландшафта на городское пространство.

Здесь европейский «Urban Atlas» (Городской атлас) «Copernicus Land Monitoring Service» (Службы мониторинга земель Коперника) дает отправную точку с геоданными для землепользования для почти 700 городских районов (2012 г.). Для пространственного анализа определяется плоская структура расселения, которая затем строится по принципам полигональной геометрии на основе данных из «Urban Atlas». Классифицированные дороги и железнодорожные линии берутся из «Open Street Map» (открытой карты улиц). Для изучения были выбраны двенадцать городов с различными структурами и из разных стран. Исследование показывает, что фрагментация тела поселения по главным транспортным магистралям может быть проанализирована и измерена на основе показателя эффективного размера ячейки в общегородском масштабе. Результаты дают представление о пространственной связанности районов, особенно по сравнению с городами. Для визуализации и лучшего сравнения городов результаты можно проиллюстрировать, создав обычную сетку координат для неразделенных пространств средней величины. Эффективный размер сетки описывает степень фрагментации тела поселения и представлен как мера, в значительной степени независимая от размера города и плотности населения. Такая метрика на общегородском уровне будет дополнительным источником информации для «Urban Audit» Европейского Союза.

Городская фрагментация; разделение общества; пространственный анализ; городская метрика; эффективный размер сетки; сравнение городов; Urban Atlas; Open Street Map

Résumé

Comparaison de la fragmentation urbaine dans les villes européennes: analyse spatiale basée sur des données géographiques ouvertes

Les voies de circulation servent à relier différents lieux entre eux. Dans le même temps, elles divisent un espace en deux «parties». L'article se concentre sur l'effet de fragmentation: au sein d'un territoire urbain, les routes principales peuvent segmenter l'espace urbain en faisant office de barrières physiques, indépendamment de leur nature (trafic routier ou ferroviaire), de leur largeur et de leur hauteur (surélevées, au sol ou souterraines), et de la densité du trafic. Les principaux axes routiers peuvent, selon leur effet de barrière, altérer la qualité de vie des régions limitrophes. Cette étude n'est pas axée sur les émissions et la pollution atmosphérique, mais sur l'effet des barrières en termes de «séparation des communautés». Elle démontre la transférabilité fondamentale des analyses structurelles de la fragmentation paysagère dans l'espace urbain.

Grâce à ses données géographiques sur l'utilisation des sols pour près de 700 régions urbaines (2012), l'«Atlas urbain» européen du «Copernicus Land Monitoring Service» constitue un bon point de départ. Pour l'analyse spatiale, une entité urbaine plane est définie et construite sous forme de polygone, en se basant sur les données de l'«Atlas urbain». Les routes et les voies ferrées classées sont sélectionnées à partir d'«Open Street Map». Douze villes de différents pays avec des structures diverses et variées ont été choisies pour servir d'études de cas. Cette étude montre que la fragmentation de l'entité urbaine par les principaux axes routiers peut être analysée et mesurée à l'échelle de l'ensemble de la ville à l'aide de l'indicateur relatif au maillage effectif. Les résultats fournissent des indications sur la cohésion territoriale de la zone urbaine, notamment par rapport à d'autres villes. Pour visualiser cela et obtenir une meilleure comparaison des villes, les résultats peuvent être illustrés en générant une grille régulière de territoires non fragmentés et de taille moyenne. Le maillage effectif décrit le degré de fragmentation de l'entité urbaine et est présenté comme une valeur de mesure largement indépendante de la taille et de la densité de la ville. Ce type de mesure à l'échelle de l'ensemble de la ville viendrait parfaitement compléter l'«audit urbain» de l'Union européenne.

Fragmentation urbaine; séparation des communautés; analyse spatiale; mesure urbaine; maillage effectif; comparaison de villes; Atlas urbain; Open Street Map