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Urban form revisited—Selecting indicators for characterising European cities

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ABSTRACT

Four out of five European citizens life in urban areas, and urban form – like the density or compactness of a city – influences daily life and is an important factor for both quality of life and environmental impact. Urban planning can influence urban form, but due to practicality needs to focus on a few indicators out of the numerous indicators which are available. The present study analyses urban form with respect to landscape metrics and population-related indicators for 231 European cities. Correlations and factor analysis identify the most relevant urban form indicators. Furthermore, a cluster analysis groups European cities according to their urban form. Significant differences between the clusters are presented. Results indicate that researchers, European administration and urban planners can select few indicators for analysing urban form due to strong relationships between single indicators. But they should be aware of differences in urban form when comparing European cities or working on planning policies for the whole of Europe.

1. Introduction

1.1. Urban form between compactness and sprawl

Urban form reveals the relationship between a single city and its rural hinterland (Grimm et al., 2008) as well as the impact of human actions on the environment within and around a city (Alberti, 2005; Environmental Protection Agency, EPA, 2001; Weng et al., 2007). This also relates to transportation patterns (Dieleman and Wegener, 2004). An ongoing debate distinguishes between the “urban sprawl” often found in North American cities versus the idealised, European “compact city” as two opposite urban forms (Dieleman and Wegener, 2004; Frenkel and Ashkenazi, 2008).

“Urban sprawl” is the large expansion of cities into surrounding areas by the creation of new low-density suburbs with detached or semi-detached housing and large commercial strips (Dieleman and Wegener, 2004; Schneider and Woodcock, 2008). This development is contested by groups such as the Smart Growth Movement, which aims at managing sprawl and steering urban development towards more compactness (see Jabareen, 2006, for an overview on such planning concepts).

The “compact city” is the opposite urban form characterised by high densities and relatively shorter distances. European cities are often found to be compact (Guerois and Pumain, 2008). However, the compact city is also an objective of urban planning (Burton, 2002) and is meant to accommodate urban development while minimising the use of undeveloped land. The compact city as a vision of urban planning is characterised by a high density of usage, short travel distances and a higher quality of life (Jenks et al., 1996). For designing policies of urban planning towards a more compact development, measuring urban form can provide a variety of information (Alberti, 1999; Batty, 2008; EPA, 2001). The idea of the compact city was integrated into the concept of sustainable urban form (Jabareen, 2006), which includes compactness amongst other aims such as sustainable transport and a diversity of potential activities within a neighbourhood.

An analysis of urban form reveals the problems and challenges of urban development. From a policy point of view, this is necessary to identify areas with a high need of policy intervention and to determine the diversity of urban developments. In the following, the relevance of urban form in European policies is highlighted.

1.2. Urban form in Europe

Analysing urban form is crucial for Europe because four out of five European citizens live in urban areas (European Commission, EC, 2006a). Furthermore, European cities have very diverse histories of urban development, especially since World War II, with the iron curtain separating capitalist and communist urban development, and the economic transition after 1990. Today, spatial planning still lies in the sovereignty of the European Union member states. Therefore, the method and extent of how spatial planning in Europe is coordinated vertically and horizontally among various levels of government, sectoral policies, and gov-

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ernmental and non-governmental organisations is organised very differently (Albrechts et al., 2003).

Accordingly, European cities and their spatial development have been receiving much attention. Starting with the "Aalborg Charter of European Cities and Towns Towards Sustainability" in 1994 (European Sustainable Cities and Towns Campaign, ESCTC, 1994), European cities and towns are recognised as key players in effective land use and development. The European Spatial Development Perspective was adopted in 1999 (EC, 1999), followed by the European Spatial Planning Observation Network as a scientific community in the field of territorial development in 2002. The Commission of the European Communities stressed the influence of cities on their environment in the "Thematic Strategy on the Urban Environment" (EC, 2006a) and adopted the Cohesion policy with the explicit aim of managing urban sprawl (EC, 2006b). Furthermore, the "Leipzig Charter on Sustainable European Cities" and the "Territorial Agenda" (European Union, EU, 2007a, 2007b) highlight the diversity of urban development in Europe and its importance for European policy. Lately, the Council of Europe (CoE, 2008) adopted the European Urban Charter II, declaring "... that we must organise our development around different types of urban form [...]".

Few comparative analyses regarding urban form in Europe have been conducted so far. A typology elaborated by the European Spatial Planning Observation Network regarding urban-rural relations in Europe (ESPON, 2005) based upon demography and land use resembles the typology found here in some respects, but does not provide a detailed and distributed view on urban form in Europe. Kasanko et al. (2006; see also European Environment Agency, EEA, 2006) analysed 15 European cities over time to characterise their dispersion. They qualitatively clustered these cities into Southern Europe, Northern or central Europe, and Western or central Europe. According to their findings, cities in Southern Europe are still today the densest and most compact cities. Cities in Northern or central Europe are, according to Kasanko et al. (2006), characterised by lower densities than Southern or Western European cities. Northern or central European cities have looser, discontinuous urban structures, and the amount of built-up area per person is higher than in other regions. Guerois and Pumain (2008) analysed the development of 54 cities in Western Europe, also using CORINE land cover. The authors used the density of built-up areas to analyse gradients from the city centre to the periphery. In sum, these very diverse analyses reveal differing concepts of and indicators for urban form.

1.3. *Definition of and indicators for urban form*

The definitions of urban form vary to a great extent in the literature. While some authors solely rely on land use/land cover to measure urban form in terms of the physical structure of a city (Herold et al., 2002; Huang et al., 2007), others also include socio-economic aspects such as population number or density (Frenkel and Ashkenazi, 2008; Kasanko et al., 2006; Tsai, 2005). Furthermore, the question of whether the sheer size of a city is one aspect of urban form (e.g. Tsai, 2005) or an independent indicator (Batty, 2008; Huang et al., 2007) is still open. However, urban form itself is mainly referred to as a property of a city and therefore static for a given point in time, while urban growth is a dynamic process that alters urban form.

For this paper, the broadest definition possible of urban form is used. Accordingly, urban form here encompasses the physical structure and size of the urban fabric as well as the distribution of population within the area. Urban form of a specific city is the result of a variety of influences, including site and topography, economic and demographic development and planning efforts in the past (Batty and Longley, 1994).

Researchers and practitioners who endeavour to quantify the urban form of a single city or a whole range of cities can choose from numerous indicators. At least two strands of discussion with respect to measuring urban form are distinguished: landscape metrics and socio-economic indicators. Landscape metrics as developed by landscape ecologists identify landscape forms. The general approach is to analyse maps of land use or cover to compute form parameters such as fragmentation or edge density. Population-related indicators for measuring urban form are also discussed in the literature, e.g. population number, population density or the administrative area of the city. Finally, some studies analyse both types of indicators in parallel. In the following, the most common studies for the different approaches are described. The focus is on indicators that can possibly be applied to a large number of cities (excluding the indicators by Galster et al., 2001) and that are applicable for a city as a whole, allowing different cities to be compared.

(1) Landscape metrics. Frequently used urban form indicators are summarised in Table 1. Recent publications include the study by Kasanko et al. (2006) who analysed the form of 15 European cities over several decades to describe their land use development with a focus on dispersion. Schneider and Woodcock (2008) quantified urban sprawl for 25 metropolitan regions worldwide, while Herold et al. (2002) described changes in urban land uses for Santa Barbara, CA. Indicators on the fractal dimension identify gradients within a city and aggregated values for clustering (Longley and Mesev, 2000; Mesev et al., 1995; Thomas et al., 2008).
(2) Socio-economic indicators. Socio-economic indicators used in recently published studies are summarised in Table 2. In her study of 25 English cities, Burton (2002) analysed compactness using socio-economic indicators in the categories of density, mix of uses, and intensification. Huang et al. (2007) compared 77 cities around the world regarding five dimensions of urban form: complexity, centrality, compactness, porosity, and density. The authors related these landscape metrics to socio-economic indicators such as the GDP per capita. Tsai (2005) used four indicators for distinguishing compactness from sprawl in his analysis of US metropolitan areas: size, density, the degree of equal distribution, and the degree of clustering. These indicators use data on employment and population. Finally, Tratalos et al. (2007) linked urban form (including socio-economic indicators) with biodiversity potential and ecosystem services for five cities in the UK.

1.4. *Aims and organisation of the study*

The overall aim of this study is to characterise and classify European cities according to their urban form. It builds upon existing studies, but greatly extends the number of cities analysed quantitatively. Considering the large number of indicators in the literature, two methods of choosing indicators are feasible: either to select a small set of indicators based upon ex ante assumptions or to analyse a broad range of indicators and determine the most appropriate indicators empirically. Most of the studies on urban form build upon a rather small set of indicators chosen beforehand. In only a few publications was the appropriateness of the selected indicators analysed by checking relationships to alternative indicators (Tsai, 2005). However this is exactly what could help to thin out the jungle of indicators and exclude indicators in a comprehensible fashion. Accordingly, the methodological aim of this study is to empirically reduce the number of indicators for urban form in Europe by analysing the relationships among urban form indicators.

Table 1
Landscape metrics for urban form in the literature.

Indicator	Measurement	Interpretation	Source	Included
Size of continuous area [area cont]	Spatial extent of continuous area [km^2]	The absolute extent of continuous area indicates the size of the dense sealed urban area.	Input for various indicators.	Yes
Size of discontinuous area [area discont]	Spatial extent of discontinuous area [km^2]	The absolute extent of discontinuous area indicates the size of the less dense sealed urban area.	Related to area cont.	Yes
Size of total area [area total]	Spatial extent of whole city [km^2]	The absolute extent of the city area indicates the size of city in its boundaries.	Input for various indicators.	Yes
Size of sealed urban area [area urban]	Spatial extent of sealed urban area [km^2]	The absolute extent of urban area indicates the size of sealed urban area in the city.	Schneider and Woodcock (2008)	Yes
Area weighted mean patch fractal dimension [AWMPFD] [MPFD]	Area weighted mean patch fractal dimension $AWMPFD = \frac{\sum_{i=1}^{i=N} 2\ln 0.25p_i/\ln s_i}{N} \times \frac{s_i}{\sum_{i=1}^{i=N} s_i}$ *si* and *pi* are the area and perimeter of patch *i*, and *N* is the total number of patches MPFD: without weighting of areas	AWMPFD indicates the raggedness of the urban boundary. It approaches 1 for simple forms and 2 for complex forms.	Herold et al. (2002) Huang et al. (2007)	Yes
Area weighted mean shape index [AWMSI] [MSI]	Area weighted mean shape index $AWMSI = \frac{\sum_{i=1}^{i=N} p_i/4\sqrt{s_i}}{N} \times \frac{s_i}{\sum_{i=1}^{i=N} s_i}$ *si* and *pi* are the area and perimeter of patch *i*, and *N* is the total number of patches MSI: without weighting of areas	AWMSI indicates the regularity of the patches. It equals 1 for circular features or square cells and increases with irregularity.	Huang et al. (2007)	Yes
Centrality index [centrality]	$\text{Centrality index} = \frac{\sum_{i=1}^{N-1} D_i/N-1}{R} = \frac{\sum_{i=1}^{n-1} D_i/N-1}{\sqrt{S/\pi}}$ *Di* is the distance of centroid of patch *i* to centroid of the largest patch, *N* is the total number of patches, *R* is the radius of a circle with area of *s*, and *s* is summarization area of all patches	The centrality index indicates the average distance of sealed urban patches with respect to the largest sealed urban patch.	Huang et al. (2007)	Yes
Compactness index [CI]	Compactness index $CI = \frac{\sum_i P_i/p_i}{N^2} = \frac{\sum_i 2\pi\sqrt{s_i/\pi}/p_i}{N^2}$ *si* and *pi* are the area and perimeter of patch *i*, *Pi* is the perimeter of a circle with the area of *si* and *N* is the total number of patches	The CI indicates compactness and is higher for more regular landscapes with a low number of patches.	Huang et al. (2007)	Yes
Compactness index of the largest patch [CILP]	Compactness index of the largest patch $CILP = \frac{2\pi\sqrt{s/\pi}}{p}$ *s* and *p* are the area and perimeter of largest patch	The CILP indicates compactness and is higher for a more regular patch.	Huang et al. (2007)	Yes

Table 1(*Continued*)

Indicator	Measurement	Interpretation	Source	Included
Share of continuous/residential land [cont/resid]	Percentage of continuous residential area over all residential area	The share cont/resid ranges from 0 to 100% and indicates the density of residential areas.	Burton (2002) Kasanko et al. (2006)	Yes*
Share of continuous/urban land [cont/urban]	Percentage of continuous residential area over all urban area	The share cont/urban ranges from 0 to 100% and indicates the density of residential areas.	It is similar to cont/resid.	Yes
Edge density [ED]	Sum of all urban edge lengths/total sealed urban area [km/km^2]	ED accounts for the length of edge relative to the area of the patch. A high ED indicates a ragged patch.	Herold et al. (2002)	Yes
Median patch size [MDPS]	Median size of sealed urban patches [km^2]	The MDPS indicates the average size of sealed urban patches.	Helpful for interpreting PSSD.	Yes
Mean perimeter-area ratio [MPAR]	Sum of each sealed urban patches perimeter/area ratio/NP [km/km^2]	The MPAR indicates the average complexity of sealed urban patches.	Related to other complexity indicators	Yes
Mean patch edge [MPE]	TE/NP [km]	The MPE indicates the average complexity of sealed urban patches.	Helpful for interpreting ED.	Yes
Mean patch size [MPS]	Mean size of sealed urban patches [km^2]	The MPS indicates the average size of sealed urban patches.	Helpful for interpreting PSSD.	Yes
Number of patches [NP]	Number of sealed urban patches in city.	The NP indicates compactness.	Input for various indicators.	Yes
[Number of districts SCD 1/2]	Number of sub-city districts in the city as reported by cities.	The number of districts SCD indicates the administrative structure of a city.	Input for various indicators.	Yes
Patch size coefficient of variance [PSCV]	PSSD/MPS	The higher the PSCV, the larger are the differences in patch size between the single sealed urban patches.	Related to PSSD.	Yes
Patch size standard deviation [PSSD]	Deviation from mean in patch size for sealed urban patches [km^2]	The higher the PSSD in km^2, the larger are the differences in patch size between the single sealed urban patches.	Herold et al. (2002)	Yes
Porosity [ROS]	Ratio of open space $ROS = \frac{s'}{s}100\%$ s' is the summarisation of all non-urban area, s is the total area	The ROS ranges from 0 to 100%. The higher the ratio of open space, the less area is urbanised.	Huang et al. (2007)	Yes
Total edge [TE]	Sum of perimeters of all sealed urban patches [km]	The TE indicates the length of all borders of sealed urban patches and measures complexity.	Input for various indicators.	Yes
Share of sealed urban area [urban/area]	Percentage of sealed urban area of total land area Herold et al. (2002): commercial & industrial area/total land area; high and low density area/total land area	The share urban/area ranges from 0 to 100%. The higher the share urban/area, the more surfaces in the city are urbanised.	Herold et al. (2002) Kasanko et al. (2006) Schneider and Woodcock (2008)	Yes
Contagion index	Sum over all patches of all classes of two probabilities (randomly, conditional) of patch (class i) being adjacent to patch (class j)	The contagion index ranges from 0 to 100% and gives the probability of a patch of the class i to be adjacent to a patch of the class j, indicating low versus highly fragmented landscapes.	Herold et al. (2002)	No**
Density of building	Number of buildings per hectare	The number of buildings per hectare indicates the density of sealed urban area.	Tratalos et al. (2007)	No No data

Table 1(*Continued*)

Indicator	Measurement	Interpretation	Source	Included
Fractal dimension	$D = \frac{1}{\log_{10} R'} \log_{10} \left[\frac{N(R')}{4}\right] \approx 2 + \frac{\log_{10} p(R')}{\log_{10} R'}$	Using this definition, fractal dimension refers to the clustering of population throughout the city. D lies between 1 and 2, with values close to 2 indicating more clustered forms.	Mesev et al. (1995)	No
	D: Fractal dimension R′ mean distance *N* (R) cumulative, spatially explicit population			No data
Proportion detached/semi-detached	Proportion of houses that are detached or semi-detached	The proportion of detached and semi-detached houses indicates settlement structure.	Tratalos et al. (2007)	No
				No data

* residential: CLC111 and CLC112. ** The contagion index refers to the relationship between all land use classes. It was excluded from this study as the focus here is solely on the form of sealed urban patches.
Column "Indicator": Abbreviations in brackets are used in subsequent tables.
Column "Source": If the cell does not contain a literature citation, the indicator has not been used explicitly in the reviewed literature. In this case, the reason for entering the indicator in the analysis is given.

The paper is organised as follows. Section 2 gives an overview of the methodology including the data sets and analysis. Section 3 describes the results, which are discussed in section 4. Finally, section 5 provides a summary and conclusions.

2. Methodology

The methodology for this study builds upon the review of urban form indicators as described above and consists of the following steps. (1) Appropriate data on the spatial delineation of the cities, socio-economic indicators and land cover were acquired and prepared (Section 2.1, Fig. 1a). (2) A minimal set of indicators of urban form was identified (Section 2.2, Fig. 1b). (3) Building upon these indicators, cities were grouped and characterised (Section 2.3, Fig. 1b). All of the statistical procedures were computed using the software package SPSS® version 14.

2.1. Data

Data provided by the Urban Audit initiative form the basis of this study. The Urban Audit initiative aims at providing economic and social statistical information for analysing pan-European urban development. Urban Audit was initiated by the Directorate-General for Regional Policy at the European Commission and is implemented with the support of Eurostat and the national statistical offices of 27 European countries. Urban Audit selected medium (50,000 up to 250,000 inhabitants) and large-sized (more than 250,000 inhabitants) cities from each participating country, including all capital cities and aiming at a broad geographical dispersion of cities. Data for around 300 indicators on three spatial levels are reported for each city: (1) the city level, (2) the larger urban zone, and (3) sub-city districts (Eurostat, 2004, 2007). The city level encompasses the administrative boundaries of the city, while the larger urban zone reflects the broader, functional urban region, often including an employment area or commuting distances. Furthermore, for both London and Paris, a so-called kernel has been defined to ease the comparison of these two metropolitan areas with other cities in Europe.

258 cities participated in the 2003/2004 Urban Audit reporting period from 1999 to 2002. 26 Turkish cities joined in 2006. Of these 284 cities, 231 provided data relevant for this study and were therefore included in the analysis (see the list of cities in the Annex and the map in Fig. 2).

The spatial delineation of the cities refers to their administrative boundaries. Data on administrative boundaries for cities participating in Urban Audit were downloaded from the Eurostat website. The 2001 data set was used because it corresponds to the socio-economic and land cover data.

Socio-economic data from the Urban Audit reporting period of 2003/2004 for the years 1999–2002 were used, matching the latest available land cover data for Europe in the year 2000. The indicators obtained from Eurostat are listed in Table 3. Indicators were used at the city level, in addition to population and area values for sub-city districts. Additionally, socio-economic indicators regarding income, education, et cetera were included for the characterisation of European cities (Tables 3 and 4).

Data of the CORINE (COoRdination of INformation on the Environment) programme of the European Commission were used for the land cover information of European cities. The CORINE programme aims at providing harmonised data on the state of the European environment. The CORINE Land Cover (CLC) project (EEA, 1995) is part of the CORINE programme and covers data on land cover in Europe. Land cover is classified into 44 classes under five headings: artificial surfaces, agricultural areas, forest and semi-natural areas, wetlands, and water bodies. For this study, raster data with a resolution of 100 per 100 meters for land cover in Europe 2000 were obtained from the European Environment Agency. During the data preparation, urban land covers were summarised to "sealed urban patches". All steps of data preparation are summarised in Fig. 1a.

2.2. Selection of a minimal set of indicators

The procedure for selecting the minimal indicators of urban form is given in the upper part of Fig. 1b. The factor analysis is the main procedure for determining minimal indicators (A4). In general, the aim of a factor analysis is to reduce the available variables by extracting common factors that influence all variables. The individual variables load onto one or more of these factors, allowing the influence of all of the factors on the variables to be estimated. There are several extraction methods leading to the factors. The principal axis factoring was chosen as the extraction method, which produces orthogonal (and therefore uncorrelated) factors. To facilitate the interpretation of the extracted factors, a Varimax rotation was estimated. It maximises the variance of the extracted factors by changing the factor loadings for the variables, but due to the rotation does not change the factors themselves. The number of factors to be extracted was determined by the Eigenvalues of the factors, so that only factors with an Eigenvalue greater than one were extracted.

Table 2
Socio-economic indicators for urban form in the literature.

Indicator	Measurement	Interpretation	Source	Included
Index of Dissimilarity in population distribution [diss2]	Index of Dissimilarity $ID = 0.5\sum_{i=1}^{N} \mid \mid X_i - Y_i \mid$ N number of sub-city districts (Urban Audit SCD level 2) X_i proportion of land in sub-city district i Y_i proportion of population in sub-city district i	The diss2 measures the distribution of population across districts compared to respective area of the district. A diss2 close to 1 indicates large differences in population density between districts, a diss2 close to 0 indicates an even distribution of population across districts.	Tsai (2005) (the author calls this index "Gini" although the Gini index has another definition)	Yes
Dwelling number [dwell]	Number of dwellings for whole city	The dwell indicates the total size of the population.	Related to pop.	Yes
Gini coefficient of population distribution [Gini2]	$Gini = \frac{\sum_{i}^{N}\sum_{j}^{N}\left\|y_i - y_j\right\|}{2N^2\bar{y}}$ N number of sub-city districts (Urban Audit SCD level 2) $\bar{y}$ mean of population density in all sub-city districts	The Gini2 compares population numbers of all districts without accounting for the area of the districts. It ranges from 0 to 1, the closer the Gini2 is to 1, the more unevenness.	Tsai (2005)	Yes
Household number [hh]	Number of households for whole city	The hh indicates the total size of the population.	Related to pop.	Yes
Density of housing [hh/area]	Number of households per area [1/km^2] Burton (2002): percentage of total housing stock made up of higher density dwellings (terraces, flats, conversions)/lower density dwellings (detached and semidetached)/represented by small dwellings (1-3 rooms)/large dwellings (7 or more rooms)	The number of hh/area indicates density within the whole city.	Burton (2002) Tratalos et al. (2007)	Yes
Density of housing in urban land [hh/urban]	Households per sealed urban area [1/km^2]	The number of hh/urban indicates density in the sealed urban area.	Burton (2002)	Yes
Population number [pop]	Number of inhabitants for whole city	The pop indicates the total size of the population.	Tsai (2005)	Yes
Density of population [pop dens]	Total population/area [1/km^2]	The pop dens indicates population density for the whole city.	Huang et al. (2007) Tratalos et al. (2007) Tsai (2005)	Yes
Density of population in urban land [pop dens urban]	Population per km^2 of urban land [1/km^2] Burton (2002): +population per km^2 of residential urban land	The pop dens urban indicates population density in the sealed urban area.	Burton (2002) Kasanko et al. (2006) Schneider and Woodcock (2008)	Yes
Sealed urban area per person [urban/capita]	Sealed urban area/person [m^2/person]	The amount of urban/capita indicates the urban surface related to population number.	Kasanko et al. (2006)	Yes
Car availability [cars]	Vehicles/1000 inhabitants	Car availability indicates welfare and transport structure.	Huang et al. (2007)	Yes[#]
GDP per capita [GDP/capita]	GDP per capita [€]	The GDP/capita indicates economic welfare.	Huang et al. (2007)	Yes[#]

Table 2(*Continued*)

Indicator	Measurement	Interpretation	Source	Included
Proportion higher education [prop high education]	Proportion of population with higher education [%] Originally in Tratalos et al. (2007): Proportion of residents classified in social group AB (more affluent and professionally qualified sectors of society in UK national census)	The prop high education indicates the level of education in the population.	Tratalos et al. (2007)	Yes*,#
IT availability [PC in hh] [www in hh]	Share of households with PC and Internet availability [%] Originally in Huang et al. (2007): Telephone lines/1000 people	IT availability indicates availability of current infrastructure.	Huang et al. (2007)	Yes**,#
Density of addresses	Number of addresses per area	The number of addresses per hectare indicates density.	Tratalos et al. (2007)	No No data
Density of buildings with addresses	Number of buildings with one or more associated addresses per area	The number of buildings per hectare indicates density.	Tratalos et al. (2007)	No No data
Mix of use	Provision of facilities - number of key facilities (newsagent, restaurant or café, takeaway, food store, bank or building society, chemist, doctors' surgery) for every 1000 residents - number of newsagents for every 10,000 residents Horizontal mix of uses: - percentage of postcode sectors containing fewer than two key facilities/four or more key facilities/six or more key facilities/all seven key facilities - variation in the number of facilities per postcode sector - overall provision and spread of key facilities: variation in the number of facilities per postcode sector divided by the average number of facilities per sector Vertical mix of uses - living over the shop: area of retail space that includes accommodation, as percentage of total retail space - mixed commercial or residential uses: number of purpose-built flats in commercial buildings, as a percentage of all purpose-built flats	The provision of facilities indicates the supply of residents with a variety of infrastructure and amenities.	Burton (2002)	No No data
Moran coefficient	$Moran = \frac{N \sum_{i=1}^{N} \sum_{j}^{N} W_{ij}(X_i - X)(X_j - X)}{\left(\sum_{i=1}^{N} \sum_{j=1}^{N} W_{ij} \right) (X_i - X)^2}$ N number of sub-city districts X_i population or employment in sub-city district i X_j population or employment in sub-city district j X mean of population or employment W_{ij} weighting (=distance) between sub-city district i and j	The Moran coefficient ranges from −1 to +1, with a value close to +1 indicating that high-density districts are closely clustered, a value close to zero meaning random scattering and a value close to −1 representing a 'chessboard' pattern of development.	Tsai (2005)	No No data

* Education level instead of social groups.
** PC and Internet availability instead of telephone lines.
\# Indicators for socio-economic characterisation of cities. Column "Indicator": Abbreviations in brackets are used in subsequent tables. Column "Source": If the cell does not contain a literature citation, the indicator has not been used explicitly in the reviewed literature. In this case, the reason for entering the indicator in the analysis is given.

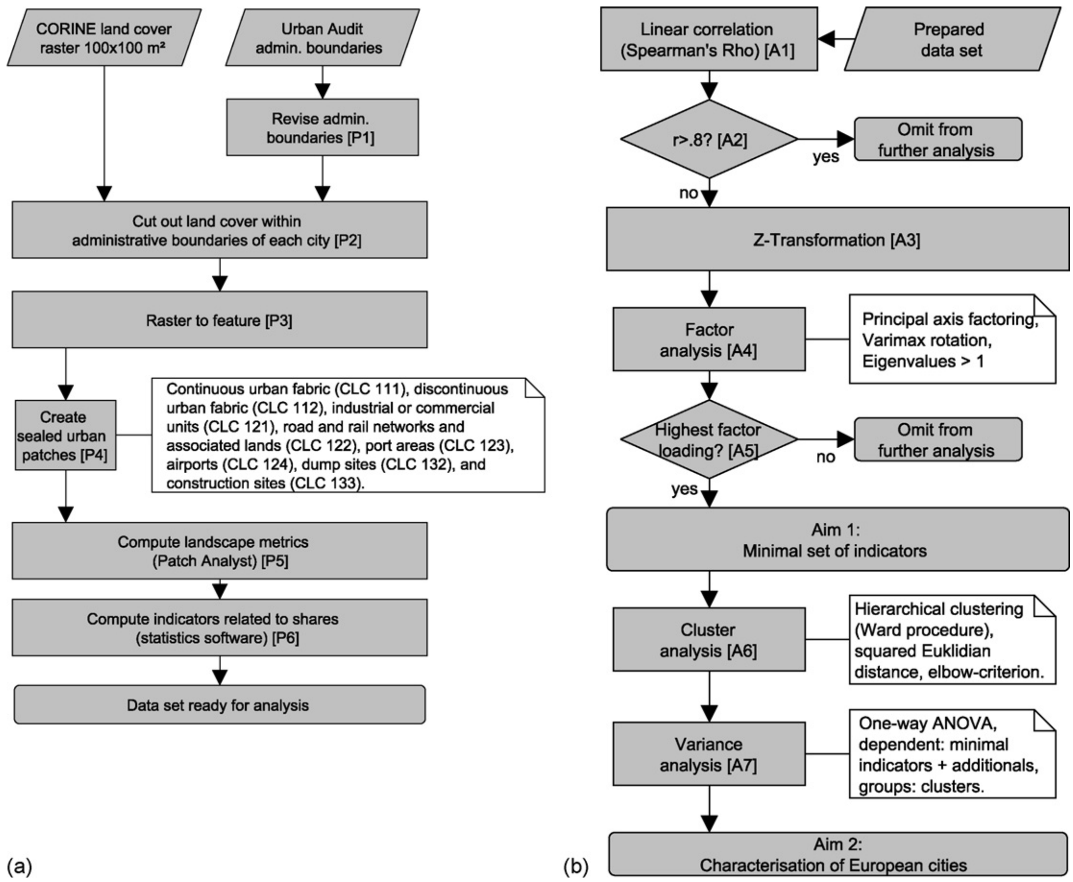

Fig. 1. (a) Methodology: Data preparation. P1. Urban Audit administrative boundaries of cities were revised. Distinct polygons for the same city were merged if these features were separated by small water bodies, roads et cetera. Polygons with holes were filled up. P2. Administrative boundaries were used to cut out CORINE land cover raster data. P3. These raster data were converted into features. P4. The CLC classes mentioned in the note were merged into a single class of "sealed urban patches". This procedure of summarising urban land covers into a single category for analysis is in line with other research on urban form (Huang et al., 2007; Galster et al., 2001). P5. Landscape metrics for this urban class were computed using the open source software "Patch Analyst" (Rempel, 2008). Patch Analyst is an extension for the ArcGIS® Software and provides the most common landscape metrics for landscape analysis. Landscape metrics were computed using the class level procedure and the joined sealed urban area as input. Class level procedure implies referring to the sealed urban patches only and not to all patches in the city. P6. Additionally, ratios like the share of sealed urban patches compared to the size of the whole city as well as Index of Dissimilarity and Gini-coefficient were computed. The latter two were computed for Urban Audit SCD level 2 (sub-districts possibly created for Urban Audit to be more comparable). (b) Methodology: Analysis. A1. Linear correlations among (1) population-related and (2) landscape metrics as well as (3) between population-related and landscape metrics were computed to reveal similarities between indicators. Spearman's Rho r_s was used as correlation measure because non-linear relationships between indicators were identified. A2. To reduce the number of indicators entering the factor analysis, indicators of urban form were omitted from further analysis, if they show strong correlations (absolute correlations >.8) to other indicators in the data set. A3. All variables were normalised (Z-transformation), so that the mean for each indicator equals 0 and the standard deviation equals 1. A4. A factor analysis was computed to identify underlying patterns of relationships between indicators. A5. Indicators which best represent the extracted factors are included into the minimal indicator set for urban form.

Table 3
Data out of Urban Audit used for this study.

Related to indicator	Name in Urban Audit	Urban Audit code	Level	No. of valid cases (total: $N = 231$)
Population-related indicators				
Area total	Total land area (km^2) according to cadastral register	en5003i	City	209
Dwell	Number of dwellings	sa1001i	City	197
hh	Total Number of Households	de3003i	City	219
Pop	Total Resident Population	de1001i	City	228
Pop	Total Resident Population	de1001i	SCD 2	197
Popdens	Population density – total resident population per square km	en5101i	City	208
Needed for diss2	Total land area (km^2) according to cadastral register	en5003i	SCD 2	124
Socio-economic indicators for characterising cities				
Cars	Number of registered cars per 1000 population	tt1057i	City	181
GDP/capita	GDP per head	ec2001i	City	208
PC in hh	Proportion of households with a PC	it1001i	City	63
Prop high education	Proportion of the resident population qualified at levels 5–6 ISCED	te2022i	City	196
www in hh	Percentage of households with Internet access at home	it1005i	City	68

See Tables 1 and 2 for abbreviations of indicators.

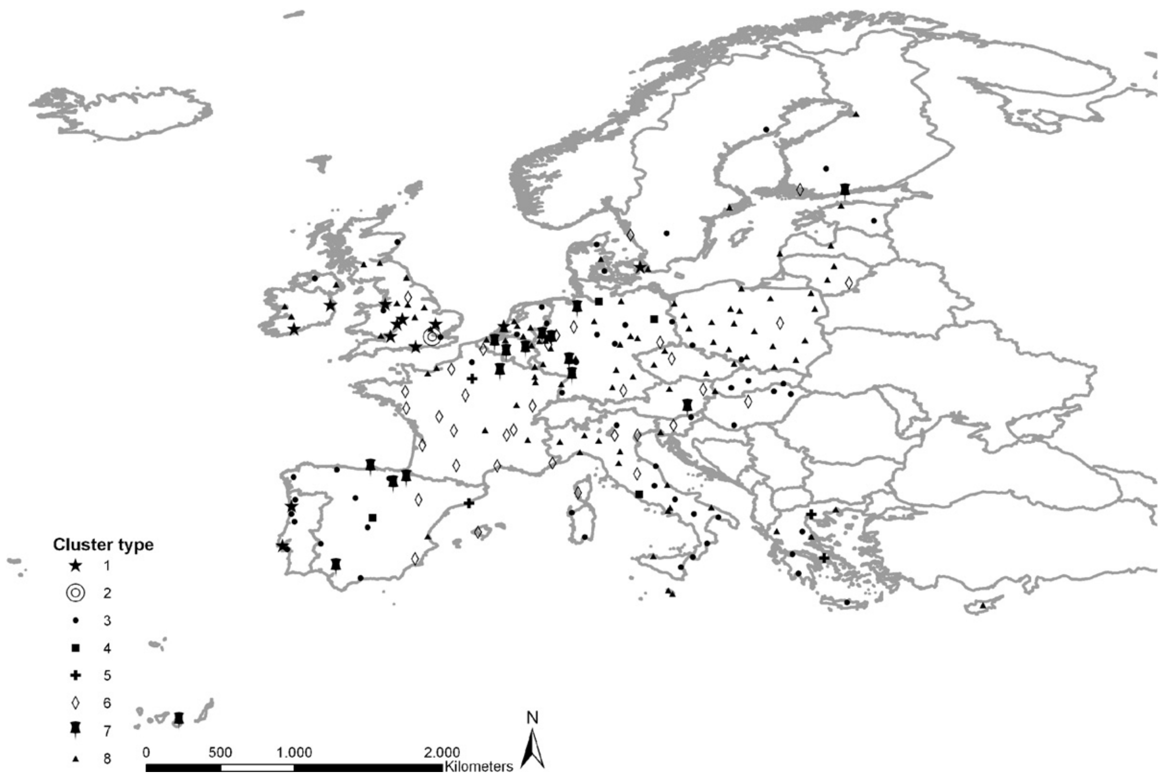

Fig. 2. Map of European cities analysed in this study with respective cluster type. Sources: Administrative boundaries and location of Urban Audit cities downloaded from Eurostat. ©EuroGeographics and ESRI for the administrative boundaries of countries.

2.3. The Characterisation of European cities

The procedure of characterising European cities according to the minimal set of indicators is displayed in the lower part of Fig. 1b and consists of the two steps (A6) cluster analysis and (A7) variance analysis.

A6. In order to compare European cities according to their urban form, a cluster analysis with the identified minimal indicator set was computed. The hierarchical clustering (Ward procedure) was applied with the squared Euclidian distance as the distance measure. The "elbow-criterion", which focuses on the percentage of variance explained as a function of the number of clusters, determined the number of clusters. According to this rule of thumb the optimal number of clusters is the number after which the marginal gain of adding one more cluster drops sharply. For this analysis, the solution with eight clusters was chosen.

A7. To characterise the cities belonging to each cluster, a one-way analysis of variance was computed, using the minimal indicator set as dependent variables and the clusters as group parameters. Additionally, the following socio-economic indicators were used as dependent variables to gain an impression of the various aspects of human welfare (Huang et al., 2007) in these clusters: the GDP per capita, proportion of population with higher education, car ownership per 1000 inhabitants, PC availability in households, and Internet availability in households.

3. Results

3.1. Reduction of indicators due to correlations

Correlations among the population-related indicators are shown in the lower left part of Table 5, and correlations among the landscape metrics are presented in the upper right part of the same table. Correlations between population-related indicators and landscape metrics are depicted in Table 6. These results are elaborated in the following paragraphs, differentiated into correlations among the landscape metrics, among the population-related metrics and between these two.

3.1.1. Correlations among the landscape metrics

Regarding correlations among the landscape metrics, the following indicators of urban form were omitted from further analysis. (1) The size of urban area was excluded due to its close relationship with size of the discontinuous urban fabric. The choice was to eliminate the size of urban area because it is the sum of the size of the discontinuous and continuous urban fabric, and it was consistent to leave the two more detailed measurements in the analysis. (2) The ratio of the share of the continuous urban fabric to the urban area was deleted in favour of the size of the continuous urban fabric because it is more straightforward to use the absolute value instead of a ratio. (3) The ratio of the share of continuous urban fabric to the residential area was removed due to its relationship with the size of the continuous urban fabric. The same reason as for the share of the continuous urban fabric to the urban area applies. (4) The share of open space was excluded because it is the inverse of the ratio of the share of the urban area to the total area. (5) The mean perimeter-area ratio was omitted because of its close relationship to the median patch size, in order to keep the absolute value instead of the ratio. (6) The two metrics, AWMPFD and AWMSI, measuring the shape complexity and irregularity are highly correlated ($r_s = .89$, $p < .001$). AWMPFD was omitted because it has lower correlations to other the indices compared to AWMSI. Without weighting the area, the MPFD and MSI indicators are not correlated, and therefore, these unweighted indicators were no longer analysed. (7) The total edge and number of patches are highly correlated ($r_s = .83$, $p < .001$), showing the geometrical relationship between the number of sealed urban patches and the sum of all the perimeters of

Table 4
Descriptive results for urban form indicators.

Indicator	N	Min	Max	Mean	SD
Landscape metrics					
Area cont [km²]	231	0.0	89.3	6.6	12.4
Area discount [km²]	231	0.0	923.6	52.6	76.6
Area total [km²]	231	18.8	2324.8	248.9	277.7
Area urban [km²]	231	7.3	1093.6	77.7	96.1
AWMPFD	231	1.2	1.4	1.3	0.0
AWMSI	231	1.5	11.8	3.6	1.3
Centrality	230	0.4	273.1	8.6	27.3
CI	231	0.0	0.6	0.1	0.1
CILP	231	0.1	0.8	0.3	0.2
Cont/resid [%]	231	0.0	100.0	14.4	21.9
CONT/urban [%]	231	0.0	81.0	10.6	16.2
ED [km/km²]	231	0.1	2.4	1.0	0.4
MDPS [km²]	231	0.0	44.9	0.8	3.7
MPAR [km/km²]	231	1.5	42.2	21.8	7.2
MPE [km]	231	2.0	59.6	9.9	6.6
MPFD	231	1.2	1.3	1.3	0.0
MPS [km²]	231	0.3	44.9	4.2	4.9
MSI	231	1.4	2.4	1.6	0.2
NP	231	1.0	124.0	26.7	23.3
Number districts SCD 1	18	2	37	13.3	10.2
Number districts SCD 2	220	3	624	23.5	45.7
PSCV	231	0.0	785.9	322.6	134.7
PSSD [km²]	231	0.0	132.2	11.9	12.3
ROS [%]	231	5.7	98.0	61.9	21.0
TE [km]	231	23.9	1512.9	206.1	183.1
Urban/area [%]	231	2.0	94.3	38.1	21.0
Population-related indicators					
Area total (UA) [km²]	209	23.4	2317.0	253.8	278.9
diss2	124	0.0	0.7	0.4	0.1
Dwell [1000]	197	15.0	1869.9	180.6	224.1
Gini2	197	0.0	0.4	0.2	0.1
hh [1000]	219	11.8	3016.0	190.2	290.0
hh/area [no. per km²]	219	22.6	10 290.4	968.2	1158.3
hh/urban [no. per km²]	219	764.5	12 931.3	2305.4	1338.6
Pop [1000]	228	30.8	7172.1	414.7	636.6
Popdens (UA) [no. per km²]	205	44.9	15 246.9	2049.0	1769.0
Popdens [no. per km²]	228	45.0	20 515.3	2242.6	2684.2
Popdens urban [no. per km²]	228	1800.2	24 745.3	5430.8	3273.4
Urban/capita [m² per capita]	228	40.4	555.5	226.3	91.1
Socio-economic indicators for characterising cities					
Cars [no. per 1000 inhabitants]	181	186.2	698.6	395.8	105.0
GDP/capita [€ per capita]	208	2513.0	69 875.0	22 389.7	13 118.7
PC in hh [%]	63	8.6	67.0	37.2	15.0
Prop high education [%]	196	4.8	32.3	16.1	5.2
www in hh [%]	68	1.3	63.0	29.2	14.0

SD: standard deviation. SCD: Sub-city district in Urban Audit. (UA): value as reported by cities in Urban Audit. See Tables 1 and 2 for abbreviations of indicators.

all the sealed urban patches. Only the latter indicator was kept for further analysis because it is even easier to measure than the total edge. (8) The mean patch edge was excluded because of its high correlation with the mean patch size. The mean patch size was kept because practitioners are more used to working with the surface area than with the perimeter of a patch, e.g. when describing it. (9) A close relationship exists between the mean patch size and the patch size standard deviation ($r_s = .85$, $p < .001$). The latter was omitted from further analysis because the mean patch size is easier to understand. (10) The compactness index was omitted instead of the number of patches because the latter is easier to measure.

3.1.2. Correlations among the population-related indicators

Regarding the correlations among the population-related indicators, the following indicators of urban form were omitted from further analysis. (1) The three population-related indicators, the population number, number of households and number of dwellings, are closely related with $r_s > .98$ ($p < .001$). This close relationship is in accordance with findings by Tratalos et al. (2007), who found a high (also Spearman rank) correlation of .97 between the household density and population density for five UK cities. Accordingly, the number of dwellings and number of households were omitted from further analysis because the population number is more often used in the literature and is available more often. The same holds for the two indicators, the proportion of households per total area and the proportion of households per urban area. (2) The computed population density (reported population number divided by area of the city) was favoured instead of the reported population density for Urban Audit because more data on the absolute population numbers were available than for population density. (3) The indicator of the population density per urban area was omitted because of its inverse relationship to the urban area per capita. The latter was retained because per capita values are presumably easier to communicate to practitioners.

3.1.3. Correlations among the landscape metrics and population-related indicators

Only two indicators were excluded because of the correlations between the landscape metrics and population-related indicators. (1) The indicator of the area of the city (reported) as reported by cities in the Urban Audit data was excluded because it has a tight relationship ($r_s = .97$, $p < .001$) to the landscape metric area of the

Table 5

Correlations among socio-demographic indicators and landscape metrics respectively.

	Area total	Area urban	Urban/ area	Discont	Cont	Cont/ urban	Cont/ resid	ROS	AWMSI	MSI	MPAR	MPFD	AWMPFD	TE	ED	MPE	MPS	NP	MDPS	PSCOV	PSSD	CILP	CI	Centrality
Area total	1.00	.64***	−.37***	.57***	.26**	−.05	−.03	.37***	.37***	−.13	−.04	−.05	.31***	.80***	−.45***	−.18**	−.18**	.76***	−.01	.58***	.13	−.36***	−.77***	.24***
Area urban		1.00	.40***	.91***	.35***	−.13	−.12	−.40***	.65***	−.04	.23***	.15	.35***	.88***	.16	.29***	.40***	.56***	−.21**	.66***	.74***	−.31***	−.56***	.04
Urban/area			1.00	.37***	.19**	−.01	−.04	−1.00***	.29***	.09	.36***	.25***	.00	.06	.76***	.60***	.74***	−.27***	−.25***	.03	.72***	.08	.28***	−.27***
Discont				1.00	.11	−.33***	−.34***	−.37***	.68***	.03	.19**	.14*	.39***	.82***	.18**	.31***	.39***	.50***	−.16*	.61***	.70***	−.34***	−.50***	−.03
Cont					1.00	.85***	.85***	−.19***	.19**	−.05	.11	.05	.06	.26***	.01	.12	.20**	.16*	−.13*	.23***	.30***	−.10	−.16*	.00
Cont/urban						1.00	1.0***	.01	−.10	−.04	.04	.03	−.08	−.16**	−.09	−.02	.00	−.10	−.09	−.07	−.05	.05	.10	.00
Cont/resid							1.00	.04	−.11	−.05	.03	.02	−.00	−.14*	−.10	−.05	−.02	−.07	−.08	−.06	−.07	.05	.07	.02
ROS								1.00	−.29***	−.09	−.36***	−.25***	.00	−.06	−.76***	−.60***	−.74***	.27***	.25***	−.03	−.72***	−.08	−.28***	.27***
AWMSI									1.00	.21**	.29***	.35***	.89***	.67***	.34***	.34***	.26***	.36***	−.29***	.66***	.59***	−.45***	−.36***	.01
MSI										1.00	−.35***	−.03	.28***	−.04	.16	.62***	.36***	−.37***	.43***	−.38***	.18**	−.14	.34***	−.14
MPAR											1.00	.87***	.22***	.15	.31***	−.11	.03	.18**	−.86***	.36***	.23***	−.03	−.15	−.03
MPFD												1.00	.38***	.16	.33***	−.11	−.07	.19**	−.74***	.33***	.12	−.14	−.17**	−.03
AWMPFD													1.00	.54***	.26***	.12	−.06	.37***	−.24***	.56***	.22***	−.48***	−.39***	.07
TE														1.00	.06	−.01	.01	.82***	−.16	.78***	.40***	−.44***	−.83***	.16
ED															1.00	.29***	.30***	−.09	−.22***	.11	.31***	−.02	.10	−.17**
MPE																1.00	.93***	−.53***	.22***	−.30***	.73***	.00	.52***	−.26***
MPS																	1.00	−.48***	.08	−.20**	.85***	.09	.49***	−.26***
NP																		1.00	−.22***	.81***	−.07	−.36***	−1.00***	.27***
MDPS																			1.00	−.41***	−.15	.04	.19**	−.03
PSCOV																				1.00	.27***	−.38***	−.80***	.18**
PSSD																					1.00	−.12	.07	−.17**
CILP																						1.00	.38***	.37***
CI																							1.00	−.26***
Centrality																								1.00

	Area total (UA)	hh	Dwell	Pop	Popdens (UA)	Popdens	Popdens urban	Urban/capita	hh/area	hh/urban	diss2	Gini2
Area total (UA)	1.00											
hh	.50***	1.00										
Dwell	.51***	.99***	1.00									
Pop	.49***	.99***	.99***	1.00								
Popdens (UA)	−.34***	.60***	.58***	.58***	1.00							
Popdens	−.30***	.60***	.58***	.58***	.97***	1.00						
Popdens Urban	−.15	.28***	.32***	.36***	.55***	.57***	1.00					
Urban/capita	.15	−.28***	−.32***	−.36***	−.55***	−.57***	−1.00***	1.00				
hh/area	−.23***	.64***	.63***	.63***	.95***	.98***	.50***	−.50***	1.00			
hh/urban	−.10	.45***	.46***	.46***	.63***	.65***	.91***	−.91***	.65***	1.00		
diss2	.45***	.00	.00	.04	−.38***	−.29**	−.17	.17	−.35***	−.31***	1.00	
Gini2	.09	.02	.06	.01	−.10	−.11	−.10	.10	−.05	−.03	−.09	1.00

* $p < 0.5$.

** $p < .01$.

*** $p < .001$. See Tables 1 and 2 for abbreviations of indicators.

Table 6
Correlations between landscape metrics and population-related indices (Spearman's Rho).

	Area total	Area urban	Urban/ area	Discont	Cont	Cont/ urban	Cont/ resid	ROS	AWMSI	MSI	MPAR	MPFD	AWMPFD	TE	ED	MPE	MPS	NP	MDPS	PSCOV	PSSD	CILP	CI	Centrality
Area total (UA)	.97***	.62***	−.30***	.55***	.36***	.08	.10	.30***	.36***	−.12	−.06	−.07	.30***	.79***	−.39***	−.16	−.15	.74***	.00	.55***	.14	−.36***	−.74***	.23***
hh	.45***	.88***	.55***	.74***	.49***	.07	.07	−.55***	.56***	−.05	.24***	.10	.23***	.70***	.25***	.39***	.53***	.38***	−.20**	.53***	.78***	−.24***	−.37***	−.07
Dwell	.48***	.88***	.49***	.73***	.52***	.15*	.15*	−.49***	.56***	−.08	.29***	.17	.26***	.73***	.22**	.31***	.46***	.44***	−.27***	.60***	.74***	−.20**	−.42***	.02
Pop	.44***	.86***	.50***	.69***	.54***	.14*	.14*	−.50***	.54***	−.05	.25***	.12	.24***	.68***	.21**	.34***	.48***	.37***	−.22***	.52***	.73***	−.25***	−.36***	−.06
Pop dens (UA)	−.34***	.35***	.86***	.29***	.28***	.11	.08	−.86***	.28***	.00	.37***	.24***	.00	.03	.60***	.52***	.68***	−.24***	−.31***	.07	.68***	.02	.26***	−.32***
Pop dens	−.39***	.31***	.88***	.23**	.33***	.20**	.17*	−.88***	.23***	.06	.32***	.20**	−.02	−.02	.64***	.54***	.68***	−.30***	−.23***	.00	.64***	.04	.31***	−.31***
Pop dens urban	−.22**	−.10	.18**	−.24***	.41***	.48***	.47***	−.18**	−.05	−.03	.07	.00	−.08	−.23***	.03	.15	.19**	−.25***	−.10	−.12	.11	−.02	.26***	−.24***
Urban/capita	.22**	.10	−.18**	.24***	−.41***	−.48***	−.47***	.18**	.05	.03	−.07	.00	.08	.23***	−.03	−.15	−.19**	.25***	.10	.12	−.11	.02	−.26***	.24***
hh/area	−.32***	.38***	.90***	.31***	.29***	.11	.08	−.90***	.27***	.01	.31***	.17	−.01	.06	.64***	.54***	.69***	−.23***	−.25***	.06	.67***	.05	.24***	−.26***
hh/urban	−.19**	.04	.32***	−.08	.36***	.37***	.36***	−.32***	.02	−.08	.10	−.01	−.07	−.13	.14	.22**	.30***	−.21**	−.12	−.05	.24***	.04	.22**	−.20**
diss2	.37***	.12	−.37***	.08	.20*	.18*	.20*	.37***	.02	.15	−.18	−.04	.11	.30***	−.22	−.19	−.25**	.35***	.19	.21	−.18	−.37***	−.37***	−.09
Gini2	.12	.04	−.06	−.05	.07	.06	.06	.06	−.06	−.07	−.05	−.04	−.08	.04	−.17	−.09	−.05	.10	−.02	.06	.00	.21**	−.09	.30***

* $p < 0.5$.
** $p < .01$.
*** $p < .001$. See Tables 1 and 2 for abbreviations of indicators.

city. The correlation does not equal one due to the corrections necessary for the spatial data set described in section 3.1. (2) The indicator of the share of urban per total area was omitted because of its high relationship to the population density ($r_s = .88$, $p < .001$). The latter was retained because it is one of the standard indicators in the literature.

3.1.4. *Interim result: the indicator pool after correlation*

The 16 remaining indicators of urban form entering the factor analysis are: the area of the city, area of the continuous urban area, area of the discontinuous urban area, AWMSI, edge density, mean patch size, number of patches, median patch size, patch size coefficient of variance, compactness index of the largest patch, centrality, population number, population density, urban area per person, index of dissimilarity in the population distribution and the Gini-coefficient for the population distribution. They are listed in Table 7, which reports the results of the factor analysis.

In the following, the second step in reducing the indicators, which builds upon this factor analysis, is described.

3.2. *The reduction of indicators due to the factor analysis*

3.2.1. *Extracted factors*

In the factor analysis, six factors with Eigenvalues greater than one were extracted. They explain about 66% of the variance in the overall data set. The first row in Table 7 summarises the variance in the data set explained by each factor. The communalities of all indicators are shown in the last column in Table 7, and they represent the amount of variance in a variable that is explained by all factors. The compactness index of the largest patch, the centrality, the index of dissimilarity in the population distribution and the Gini-coefficient for the population distribution have rather low communalities; in this case, less than half of their variance is described by the extracted factors.

In Table 7, the factor loadings of all indicators are shown. The main loadings on factor I are area of the discontinuous urban fabric and the population number, with factor loadings around .9. The indicators with moderate factor loadings on factor I include the area of city, the area of the continuous urban fabric, the number of patches, AWMSI and PSCV. All variables with high loadings on this factor are related to the size of the city. Accordingly, factor I is called “size”. The factor “size” explains about 22% of the variance in the data set.

The main loadings on factor II are the population density, the area of the continuous urban fabric and the urban area per person with moderately sized loadings. These indicators relate mainly to density, and therefore this factor is called “density”. The factor “density” explains about 12% of the variance.

The main loadings on factor III are the mean patch size and the median patch size with factor loadings of around .8. Given the same total amount of sealed urban surface in a city, higher mean or median patch sizes indicate that land covers in that region are less dispersed and more clotted. Therefore, factor III is called “clustering”. The factor “clustering” explains about 10% of the variance in the data set.

Factor IV is dominated by the number of patches (factor loading of .7), with further factor loadings by the total area, PSCOV and the index of dissimilarity in the population distribution (factor loadings around .5). The number of patches as well as the PSCOV and the index of dissimilarity represent the (un-)evenness of the distribution. PSCOV refers to the variance in the sealed urban patch size, while the index of dissimilarity aims at the population distribution compared to the size of the sub-city district. Therefore, this factor is called “evenness in size”. It explains about 9% of the variance in the data set.

Table 7
Factors extracted by factor analysis.

	Factor						Communalities
	I % of variance	II	III	IV	V	VI	
	22	12	10	9	8	5	
Factor loadings							
Area total	0.48	−0.06	−0.01	0.45	−0.52	0.09	0.72
Area cont	0.43	0.72	0.04	0.14	−0.17	0.11	0.76
Area disc	0.92	0.06	0.10	0.04	−0.09	−0.04	0.87
AWMSI	0.80	−0.03	−0.04	0.07	0.24	−0.14	0.73
ED	0.13	0.09	0.10	−0.09	0.83	0.03	0.73
MPS	0.19	0.19	0.82	−0.35	0.03	−0.06	0.86
NP	0.49	−0.08	−0.20	0.67	−0.01	0.11	0.75
MDPS	−0.14	0.07	0.82	0.09	0.07	−0.07	0.72
PSCOV	0.69	−0.03	−0.31	0.46	0.19	0.06	0.83
CILP	−0.22	0.03	0.05	−0.32	−0.02	0.56	0.47
Centrality	0.01	−0.06	−0.05	0.03	0.15	0.35	0.15
Pop	0.84	0.49	0.06	0.04	−0.14	−0.01	0.98
Pop dens	−0.01	0.75	0.34	−0.10	0.24	0.08	0.75
Urban/capita	0.04	−0.67	0.01	0.19	−0.07	0.23	0.55
diss2	−0.01	−0.09	0.00	0.57	−0.17	−0.25	0.42
Gini2	0.02	0.00	−0.04	−0.01	−0.11	0.45	0.22

Factor loadings of principal axis factoring with Varimax rotation.
- Light grey: 0.5 ≤ absolute factor loading <0.7.
- Dark grey: 0.7 ≤ absolute factor loading.
See Tables 1 and 2 for abbreviations of indicators.

The main loading on factor V is the edge density. The total area has a medium-sized factor loading on this factor. The edge density is the quotient of all urban edges divided by the total area of the city. Therefore, it represents both the sheer size of the sealed urban patches and their complexity. The factor "edge density" explains about 8% of the variance.

The two indicators loading on factor VI are the compactness index of the largest patch and the Gini-coefficient (factor loadings of about 0.5). The Gini-coefficient refers to the population distribution among sub-city districts (without accounting for the size of the districts), while the compactness index of the largest patch describes the shape of the city centre. With respect to the latter, factor VI is called "compactness". The factor "compactness" explains about 5% of the variance in the data set.

3.2.2. *The minimal set of indicators of urban form*

For the minimal set of indicators of urban form, the indicator with the highest factor loading per factor was chosen. For the first factor, which explains about twice the variance in the data set than all other factors, two indicators were selected. Therefore, the minimal set of indicators for urban form consists of seven indicators: the area of the discontinuous urban fabric, edge density, mean patch size, number of patches, compactness index of the largest patch, population number, population density. These indicators were used for clustering and characterising European cities.

3.3. *The clustering and characterisation of cities*

A cluster analysis using the minimal set of seven indicators was conducted. The solution leading to eight clusters of European cities was selected because one could identify a clear step of increasing error variance at the eighth cluster. The list of cities provided in the appendix and Fig. 2 also include the classification of cities into the eight clusters. Table 8 shows the results for the variance analysis and the comparison of means in order to test the differences among the clusters. A variance analysis indicates that the differences of means between the clusters are statistically significant for all variables that were included in the cluster analysis.

Cities classified into cluster 1 are characterised by an above-average mean patch size, a smaller number of patches and a higher population density. Therefore, cities in this cluster tend to be more clotted than the average because they have only few, but large sealed urban patches. This hints at compact development, however with several centres as opposed to a single one. Half of the twelve cities in cluster 1 are situated in the UK. The remaining cities are located in Denmark, Ireland, the Netherlands and Portugal.

Cluster 2 only consists of one big city, namely London. London is characterised by a very large area of discontinuous urban fabric, a large population number, a large mean patch size and a less than average compactness index of the largest patch.

Cities belonging to cluster 3 mainly show below average values compared to the overall sample. They are characterised by a lower edge density, population density, population number and area of discontinuous urban fabric. These smaller cities are scattered over a variety of European countries including Italy, Germany and Spain.

Cities in cluster 4 display a higher than average population number, higher area of discontinuous urban fabric and high number of patches. These specificities hint at a scattered, low-density spatial development. The four cities forming this cluster are large metropolitan areas: Rome, Madrid, Berlin and Hamburg.

The four cities (Athens, Thessaloniki, Paris, Barcelona) in cluster 5 are characterised by a very high population density, high population number and higher mean patch size, while the number of patches is lower than the average. Although both clusters 4 and 5 represent large metropolitan areas, cities in cluster 5 are denser and have less urban area that is concentrated in larger sealed urban patches.

Cluster 6 is dominated by French cities, with 16 out of 36 cities in this cluster located in France. The remaining cities are situated in other countries including Germany, Spain and Italy. These cities are characterised by a higher number of patches, a lower compactness index of the largest patch and a higher area of discontinuous urban fabric. Compared to cities in cluster 4, they are smaller.

Cluster 7 is mainly characterised by a higher compactness index of the largest patch and a high edge density. These characteristics indicate a regularly shaped large patch, but simultaneously more ragged, smaller sealed urban patches. The 16 cities in this cluster stem amongst others from Germany, Spain, and Belgium.

The large number of cities ($N = 99$) in cluster 8 only slightly differs from the average of the sample, mainly because of a higher edge

Table 8
One-way analysis of variance for clusters of European cities.

		Cluster 1	2	3	4	5	6	7	8
		N							
		12	1	56	4	4	36	16	99
	Urban form indicators								
	ANOVA F	M (SD) cluster 1	M (SD) cluster 2	M (SD) cluster 3	M (SD) cluster 4	M (SD) cluster 5	M (SD) cluster 6	M (SD) cluster 7	M (SD) cluster 8
Area discont	115.7 (7, 220), 0.000	−0.01 (0.66)	11.37*	−0.40 (0.19)	2.66 (1.79)	−0.61 (0.04)	0.53 (0.73)	−0.19 (0.42)	−0.14 (0.34)
ED	30.0 (7, 220), 0.000	0.45 (0.58)	−0.12*	−1.14 (0.62)	−0.38 (0.69)	0.37 (0.57)	−0.04 (0.76)	1.01 (1.25)	0.44 (0.69)
MPS	46.9 (7, 220), 0.000	2.93 (2.07)	2.54*	−0.37 (0.45)	0.06 (0.47)	1.90 (1.09)	−0.37 (0.39)	−0.08 (0.46)	−0.10 (0.47)
NP	73.1 (7, 220), 0.000	−0.98 (0.11)	1.64*	−0.35 (0.42)	2.85 (1.45)	−0.92 (0.19)	1.61 (0.84)	−0.33 (0.50)	−0.30 (0.50)
CILP	25.2 (7, 220), 0.000	0.11 (0.63)	−1.65*	0.17 (1.00)	0.31 (1.52)	0.76 (0.64)	−0.74 (0.57)	2.11 (0.41)	−0.18 (0.68)
Pop	123.3 (7, 220), 0.000	−0.05 (0.40)	10.62*	−0.41 (0.13)	3.52 (1.11)	1.24 (1.21)	0.30 (0.70)	−0.19 (0.27)	−0.14 (0.38)
Pop dens	132.6 (7, 220), 0.000	0.79 (0.53)	0.86*	−0.54 (0.17)	0.35 (0.54)	6.16 (0.77)	−0.31 (0.37)	0.22 (0.64)	0.01 (0.53)
	Socio-economic indicators								
	ANOVA F	M (SD) cluster 1	M (SD) cluster 2	M (SD) cluster 3	M (SD) cluster 4	M (SD) cluster 5	M (SD) cluster 6	M (SD) cluster 7	M (SD) cluster 8
GDP/capita	2.7 (7, 197), 0.012	0.43 (0.87)	1.02*	−0.30 (0.84)	0.32 (0.78)	2.02 (2.26)	0.14 (0.60)	0.27 (0.82)	−0.05 (1.15)
Prop high education	1.6 (7, 187), 0.153	0.19 (1.17)	1.30*	−0.26 (1.07)	0.15 (0.75)	0.54 (0.12)	0.32 (0.88)	0.39 (1.25)	−0.06 (0.96)
cars	0.0 (187, 5), 0.000	−0.67 (0.55)	−0.73*	0.15 (1.12)	0.65 (1.95)	−1.26*	0.35 (0.64)	0.05 (0.30)	−0.12 (1.05)
PC in hh	0.9 (5, 57), 0.471	0.14 (0.02)	§	−0.10 (1.09)	0.97 (0.93)	§	0.21 (1.21)	0.38 (0.72)	−0.19 (0.98)
www in hh	0.0 (57, 5), 0.000	0.28 (0.43)	0.98*	0.28 (1.17)	§	§	−0.19 (1.03)	−0.17 (0.97)	−0.17 (1.08)

M: mean, SD: standard deviation. See Tables 1 and 2 for abbreviations of indicators.

* Only one case available, therefore no SD.

§ No data available. ANOVA: F (degrees of freedom (df) between groups, df within groups), significance level. Means and standard deviations refer to the Z-scores of all values. Therefore, deviations from 0 indicate values higher or less than the average in the overall sample.

density and a lower number of patches. They have few, but ragged sealed urban patches. Cities are located in Poland, Germany, Italy, France and other countries.

A variance analysis with further socio-economic indicators on welfare (see Table 8) showed significant results only for the indicator GDP per capita. The four cities in cluster 5 and to a lesser extent London (cluster 2) have a very high GDP per capita compared to the average of the sample.

4. Discussion

The discussion addresses the issues data quality (4.1), spatial delineation of cities (4.2), the procedure of defining the minimal indicators set (4.3), the comparison of European cities (4.4) and, finally, the relationship between urban form and human welfare (4.5).

4.1. Data quality

The quality of socio-economic Urban Audit data needs to be considered when discussing the data quality of this study. Based upon experiences in the Urban Audit pilot phase for the 1990s, national statistical institutes participated in coordinating the data reporting and ensuring the data quality. Therefore, the data used for this study, which originate from the 2003 to 2004 data collection, have been checked for quality by the national statistical institutes. Finally, Eurostat inspected the reported data regarding anomalies in the ranges of the reported values (Eurostat, 2004). There are no indications for systematic errors in the data reporting (that data for a certain indicator is always reported too high, too low or varies systematically across cities). Non-systematic errors therefore increase noise in the data set and reduce the size of correlations.

Using landscape metrics, in general (Li and Wu, 2004) and for measuring urban form (Tsai, 2005), has some disadvantages. Moreover, the present study is dependent on the quality of the land-use data sets used. EEA (2006) claims an accuracy of the CORINE land cover of approximately 87% (with 22 out of 44 classes being validated). In this study, only urban classes, which partially belong to the classes with the highest reliability, were used. Moreover, the majority of classification errors occurred at levels two and three of the CORINE classification. Accordingly, aggregating the CLC urban classes into a single urban land cover has produced a more reliable data set of urban land cover.

4.2. Spatially delineating cities

One of the challenges of this study was to consistently define the spatial borders of the cities. The approach was to work with the administrative boundaries of the cities in order to have consistent socio-economic data for the delineation used for computing the spatial metrics. The administrative area and the sealed urban area values showed different behaviours with population-related indicators. The sealed urban area of a city is more important than the size of the administrative unit itself when looking at the number of inhabitants because it correlates highly with the sealed urban area, whereas the correlation with the administrative area is only half as large. However, the population density shows a surprising effect. It is negatively correlated with the administrative area of the city but positively correlated with the sealed urban area. The latter is immediately plausible because larger cities tend to have higher densities. The former is probably the result of incorporating small communities into small to medium-sized cities in order to increase the population number of this city, a development that results in rather low population densities accompanied by comparably large administrative areas. In summary, both approaches have clear advantages, and there does not seem to be a single appropriate method of delineating a city in terms of urban form.

When comparing cities internationally, the overall administrative set-ups of nations add to the complexity of the problem (Turok and Mykhnenko, 2007). This is partly reflected by the choice of the Urban Audit initiative to solely include cities with more than 50,000 inhabitants, so as not to confound the data set with different national definitions of what actually counts as a “city”. Nevertheless, analysing both the administrative areas and the population number per nation reveals national differences, such as smaller cities in terms of both area and population in Ireland or Greece, or a few Scandinavian cities encompassing large rural areas. Similar concerns of course hold for the sub-city districts. This was partly remedied in this study by using the SCD level two and not the official administrative districts of the cities.

Future research on analysing more socio-economic data for various spatial extents of a single city could increase our understanding of the importance of the spatial delineations of a city, including scale-effects for computing landscape metrics (Li and Wu, 2004).

4.3. Defining the minimal indicators set

This study presented a statistical selection procedure for quantitative indicators of urban form. It builds upon three assumptions: no major indicator was left out, all indicators in the analysis are relevant, and after the statistical selection, the indicators are not redundant.

Assumption (1): All major indicators were included in the original data set. The broad indicator set entering the analysis builds upon a literature review covering a range of disciplines and approaches (section 1). Furthermore, the indicators were solely excluded due to methodological and data availability reasons. Therefore, all major indicators are believed to be part of the analysis.

Assumption (2): The indicators in the original set are appropriate for measuring urban form. For instance, one could question if all indicators actually measure urban form, or if indicators such as the population number or the area of the discontinuous urban fabric for instance evaluate the urban size. This would be problematic if – and only if – the urban size was not part of urban form. Different definitions of urban form are currently being used in the literature, some including size (Kasanko et al., 2006; Tsai, 2005), some excluding it (Huang et al., 2007). In this study, no definition of “urban form” as such was elaborated beforehand that could possibly lessen the number of available indicators. On the contrary, all indicators that were discussed in the literature on urban form entered the analysis. Consequently, the statistical selection draws from the broadest indicator set possible.

Assumption (3): After the statistical selection procedure, no indicators are redundant. The main aim of this study is to determine indicators for measuring urban form empirically and not use ex ante assumptions. Accordingly, the selection procedure is based upon a stepwise statistical analysis. It ensures that the remaining indicators are not highly correlated and statistically cover different aspects of urban form, so that these indicators are not redundant from the empirical point of view in this study.

4.4. Comparing European cities

Urban form does not comply with national borders. Cities with large distances between them and different national planning regimes can be very similar in terms of their form, probably even more similar than neighbouring cities. This research therefore only partly confirms results by Kasanko et al. (2006), who found urban form differing in various regions of Europe. While these authors found very dense cities in Southern Europe, the present study not only detected dense cities there as well (cluster 5) but also a cluster of dense cities (cluster 1) located in the UK (amongst others). On the contrary, Italy, Spain and Germany account for most of the cities in cluster 3 with the lowest population density. This indicates that Southern cities can also exhibit very low densities.

More generally speaking, the analysis of a huge number of European cities reveals a much more complex picture of urban form than has been detected before. Neither can one detect "the" European compact city, nor is there a clear spatial pattern of urban form in different regions of Europe. These results were obtained using only one overall class for sealed urban surfaces (see step P.4 of Fig. 1a). Sealed urban surfaces encompass all urban sealed surfaces and smooth out differences in the shapes between single land use classes. Thus, the complexity of urban form would increase if one considered only some sealed classes like the discontinuous or continuous urban fabric.

When considering causalities, national planning policies may play a role, as for instance demonstrated by the cluster dominated by French cities. But individual specialities and historical development obviously are also very important. Such a historical analysis has been carried out by Guerois and Pumain (2008). The results presented here are in line with their findings for Italian cities because seven out of eight Italian cities in the analysis are grouped into cluster 8 of this study. However, the Spanish cities of the Guérois and Pumain study are scattered over all the clusters found here. This indicates that spatial developments, which are similar in terms of their change rates, can build upon different points of origin. A future strand of research should investigate the different development paths of cities with similar change rates and/or similar urban form to test this hypothesis. Researchers should also consider using urban simulation models. Simulation models generate land use changes with different assumptions concerning the driving forces for urban development. Analysing the modelling results for a variety of cities could enhance our understanding of the importance of different combinations of change rates and boundary conditions for urban form.

4.5. *Urban form and human welfare*

The variance analysis for the relationship of urban form and human welfare showed statistically significant results only for the GDP per capita. One can conclude that European cities with a high absolute number of inhabitants and a high density also have a higher welfare. This does not hold for a worldwide comparison. Huang et al. (2007) found a negative, medium-sized correlation between the GDP per capita and the population density ($r = -.5$, $p < .05$). The reason for this difference in results is very likely the range of cities analysed in both studies. Huang et al. (2007) analysed urban areas worldwide, while the present study focused on European cities. For a worldwide analysis, the cities with very high population densities are mega-cities with a low GDP per capita and high population numbers (Kraas, 2007).

The European positive relationship among the population number, density and GDP per capita still leaves us with open questions. First of all, correlation does not mean causality. So we cannot conclude out of this study that GDP results from density or vice versa. They may also coincide due to the same political constraints or economic developments. A thorough historical analysis including the socio-economic and governance aspects of urban form could improve our understanding of the driving forces and their relationships. Second, if one takes these correlations as causalities, the economies of scale do seem to work for the European case, so that disproportionally more GDP per capita can be produced with more people. However, one wonders if the positive relationship might in fact be only the first half of a U-shaped function, so that the GDP per capita decreases again after a peak. In this case, urban planners may be ill-advised to attempt to increase the GDP by increasing population numbers. Again, an interdisciplinary analysis of urban form integrating economic and population development, governance structures and other driving forces could bring forward our understanding of evolving urban form.

5. Summary and conclusions

The methodological aim of this paper was to identify a minimal set of indicators for urban form in Europe. To accomplish this, 231 cities across Europe were analysed in terms of their urban form, applying landscape metrics and population-related indicators. Combining the CORINE Land Cover data set with population-related data out of the Urban Audit initiative revealed many high correlations between urban form indicators. A factor analysis led to six main factors: the size, density, clustering, evenness in size, edge density, and compactness. In combination, they account for approximately 66% of all variance in the data set. The stepwise procedure using the correlations and factor analysis revealed a minimal indicator set for urban form consisting of seven indicators: the area of the discontinuous urban fabric, edge density, mean patch size, number of patches, compactness index of the largest patch, population number, and population density. Therefore, future research can select these indicators out of the rather large pool that is currently being discussed in the literature.

The overall aim was a characterisation of European cities according to their urban form. To accomplish this, a cluster analysis was performed using the minimal indicator set for urban form. Eight clusters of European cities were identified. An analysis of variance showed that statistically significant differences exist with respect to urban form among the cities. These differences have practical implications for policy making on the European level and for urban planners in single city regions who seek to compare their cities with those in other European countries. On the one hand, comparisons regarding urban form among European cities can focus on very few indicators, thereby reducing the efforts of data gathering and data analysis. However, comparisons among European cities should be pursued very carefully because they are very diverse. Groups of European cities with similar urban form do not stick to national borders. In fact, two cities that are far apart on a European map may be more similar with respect to their urban form than two cities of the same nationality. This diversity of European cities must be considered when comparing them and designing urban policies for such a broad range of cities.

To complicate things even more, not only the urban form but also the governance structures are very different in Europe with respect to spatial planning. This is particularly important for urban form because spatial planning sets the framework for urban development and can – if implemented strictly – have a huge influence on urban form. Therefore, policy makers not only have to keep in mind the current urban form of cities in Europe but also the governance structures that are applied in different cities. Comparative research regarding the influence of governance structure on urban form could inform policy makers on helpful governance structures to reach their goal of a compact city.

Future research regarding urban form of European cities should compare different ways of delineating cities like administrative boundaries, urbanised areas as detected by remote sensing or buffer zones around central business districts. Furthermore, the appropriateness of the minimal indicator set for world regions other than Europe should be checked. An interdisciplinary study of urban form including landscape metrics, socio-economic factors and governance structures combined with a historical analysis would greatly enhance the understanding of emerging urban form. Finally, research should also elaborate ways of integrating questions of urban shrinkage and its implications for the analysis of urban form as this phenomenon becomes increasingly relevant for European cities.

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Appendix A.

List of cities analysed in this study and respective cluster in brackets.

Northern Europe
Aalborg (3)
Aarhus (8)
Aberdeen (3)
Belfast (8)
Birmingham (1)
Bradford (*)
Bristol (1)
Cambridge (1)
Cardiff (8)
Cork (1)
Derry (3)
Dublin (1)
Edinburgh (8)
Exeter (*)
Galway (8)
Glasgow (8)
Göteborg (6)
Gravesham (3)
Helsinki (7)
Jönköping (3)
Kaunas (8)
København (1)
Leeds (6)
Leicester (8)
Liepaja (8)
Limerick (8)
Lincoln (8)
Liverpool (1)
London (2)
Malmö (8)
Manchester (8)
Newcastle upon Tyne (8)
Odense (3)
Oulu (8)
Panevezys (8)
Portsmouth (1)
Riga (8)
Sheffield (8)
Stevenage (8)
Stockholm (8)
Tallinn (8)
Tampere (3)
Tartu (3)
Turku (6)
Umeå (3)
Vilnius (6)
Worcester (1)
Wrexham (3)

Appendix A (*Continued*)

Eastern Europe
Banská Bystrica (3)
Bialystok (8)
Bratislava (8)
Brno (8)
Budapest (6)
Bydgoszcz (8)
Gdansk (8)
Gorzów Wielkopolski (8)
Jelenia Góra (3)
Katowice (8)
Kielce (8)
Konin (8)
Kosice (3)
Kraków (*)
Lodz (8)
Lublin (8)
Miskolc (3)
Nitra (3)
Nowy Sacz (8)
Nyíregyháza (3)
Olsztyn (8)
Opole (8)
Ostrava (8)
Pécs (3)
Plzen (8)
Poznan (8)
Praha (6)
Rzeszów (8)
Suwalki (8)
Szczecin (8)
Torun (8)
Ùstí nad Labem (8)
Warszawa (6)
Wroclaw (8)
Zielona Góra (8)
Zory (3)

Southern Europe
Ancona (3)
Athina (5)
Aveiro (3)
Badajoz (3)
Barcelona (5)
Bari (8)
Bologna (8)
Braga (3)
Cagliari (3)
Campobasso (3)
Caserta (8)
Catania (3)
Catanzaro (3)
Coimbra (3)
Cremona (8)
Firenze (8)
Genova (8)
Gozo (8)
Ioannina (8)
Irakleio (3)
Kalamata (3)
Kavala (8)
l'Aquila (3)
Larisa (3)
Las Palmas (7)
Lefkosia (8)
Lisboa (1)
Ljubljana (6)
Logroño (7)
Madrid (4)
Málaga (3)
Maribor (3)
Milano (8)
Murcia (6)
Napoli (8)
Oporto (1)
Oviedo (3)
Palermo (8)
Palma de Mallorca (6)

Appendix A (*Continued*)

Pamplona/Iruña (7)
Patras (3)
Perugia (6)
Pescara (8)
Potenza (3)
Reggio di Calabria (3)
Roma (4)
Santander (7)
Santiago de Compostela (3)
Sassari (3)
Setúbal (3)
Sevilla (7)
Taranto (3)
Thessaloniki (5)
Toledo (3)
Torino (8)
Trento (3)
Trieste (8)
Valencia (8)
Valladolid (3)
Valletta (8)
Venezia (6)
Verona (6)
Vitoria/Gasteiz (3)
Volos (8)
Zaragoza (6)

Western Europe
Ajaccio (6)
Amiens (3)
Amsterdam (8)
Antwerpen (8)
Arnhem (8)
Augsburg (8)
Berlin (4)
Besançon (6)
Bielefeld (6)
Bochum (8)
Bonn (8)
Bordeaux (6)
Bremen (7)
Brugge (8)
Bruxelles/Brussel (8)
Caen (8)
Charleroi (7)
Clermont-Ferrand (8)
Darmstadt (3)
Dijon (8)
Dortmund (6)
Dresden (6)
Düsseldorf (8)
Eindhoven (8)
Enschede (3)
Erfurt (3)
Essen (8)
Frankfurt (Oder) (3)
Frankfurt am Main (8)
Freiburg im Breisgau (3)
Gent (7)
Göttingen (3)
Graz (7)
Grenoble (8)
Groningen (3)
Halle an der Saale (8)
Hamburg (4)
Hannover (8)
Heerlen (8)
Karlsruhe (7)
Köln (6)
Le Havre (8)
Leipzig (8)
Liège (7)
Lille (6)
Limoges (6)
Linz (8)
Luxembourg (8)
Lyon (6)
Magdeburg (3)

Appendix A (*Continued*)

Mainz (7)
Marseille (6)
Metz (8)
Mörs (7)
Mönchengladbach (8)
Montpellier (6)
Mülheim an der Ruhr (8)
München (6)
Nancy (8)
Nantes (6)
Nice (6)
Nürnberg (8)
Orléans (6)
Paris (5)
Poitiers (6)
Regensburg (8)
Reims (7)
Rennes (6)
Rotterdam (8)
Rouen (6)
s' Gravenhage (1)
Saint-Étienne (6)
Schwerin (8)
Strasbourg (8)
Tilburg (3)
Toulouse (6)
Trier (8)
Utrecht (8)
Weimar (8)
Wien (6)
Wiesbaden (3)
Wuppertal (7)

Six cities were excluded because no land cover data were available (France: Saint Denis, Pointe-a-Pitre, Fort-de-France, Cayenne; Portugal: Funchal, Ponta Delgada). In addition, 47 cities in Bulgaria, Romania, and Turkey were omitted because of missing administrative boundaries for spatial delineation of the area.

* Cities lacked enough information for entering the cluster analysis.

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