The spatial distribution and frequency of street, plot and building types across five European cities

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Abstract

Typologies have always played an important role in urban planning and design practice and formal studies have been central to the field of urban morphology. These studies have predominantly been of a historical-qualitative nature and do not support quantitative comparisons between urban areas and between different cities, nor offer the precise and comprehensive descriptions needed by those engaged in urban planning and design practice. To describe contemporary urban forms, which are more diffuse and often elude previous historic typologies, systematic quantitative methods can be useful but, until recently, these have played a limited role in typo-morphological studies. This paper contributes to recent developments in this field by integrating multi-variable geometric descriptions with inter-scalar relational descriptions of urban form. It presents typologies for three key elements of urban form (streets, plots and buildings) in five European cities, produced using statistical clustering methods. In a first instance, the resulting typologies contribute to a better understanding of the characteristics of streets, plots and buildings. In particular, the results offer insight into patterns between the types (i.e., which types are found in combination and which not) and provide a new large scale comparative analysis across five European cities. To conclude, we establish a link between quantitative analysis and theory, by testing two well-known theoretical propositions in urban morphology: the concept of the burgage cycle and the theory of natural movement.

Keywords

Typo-morphology, cluster analysis, built density, network centrality, land division

1. Introduction

Although urban typologies are ubiquitous in discourses about cities and urbanism, they are rarely related to more formal studies, but rather emanate from discourses within practice, as for instance found in expressions like ‘grid-cities’, ‘block-cities’ or ‘garden-cities’. This terminology is clearly loosely defined and does not allow for precise quantitative comparison between areas or cities. Formal descriptions and studies of typo-morphology are especially found in the interdisciplinary field of urban morphology, which over the years has produced a large and varied output of research (e.g., Caniggia and Maffei, 2001; Conzen, 1960, Panerai et al., 1999; Whitehand, 2001). However, these studies have predominantly been of a historic-qualitative kind where the central concern has been the genealogy of the urban fabric and its built objects. While this brings much understanding about how cities, urban areas and building types have evolved over time, it does not immediately support more precise comparisons or tie such descriptions to their performance. Further, typo-morphological classifications are most often derived through visual appraisal, which has proven difficult when applied to the contemporary city (Prosperi et al., 2009). To describe more diffuse urban forms, quantitative methods can play an important role, but until recently, these have had a limited part in typo-morphological studies (Moudon, 1994).

An early contribution to a quantitative approach to typo-morphology comes from Martin and March (1972). They developed a theory about the relation of three generic building types (blocks, slabs and detached houses) and urban density (Steadman, 2013). This has been further developed by Berghauser Pont and Haupt (2010), by adding a multi-variable approach to the measurement of built density and by the empirical validation of the theory (Steadman 2013). Other recent contributions to quantitative approaches in typo-morphology addressed inter-scalarity and started adopting numerical classification techniques (i.e. clustering), e.g., Berghauser Pont and Haupt (2010), Colaninno et al. (2011) and Perez et al. (2018) proposed methods for classifying buildings; Barthelemy (2015), Gil et al. (2012), Serra (2013a) and Serra et al. (2016) for streets; Demetriou et al. (2013) and Tarbatt (2012) for plots; and Hausleitner et al. (2017) and Fusco et al. (2017) for the urban fabric. These new approaches have contributed to the theory and methodology of typo-morphology by developing types based on quantification, including both multiple variables and multiple scales. It should be noted that in these studies, typologies are classifications of built structures, clustered according to the similarity of their formal structure. In most of the classifications, multiple variables are used and in only a few cases, multi-scalar descriptions of urban form are used.

This paper contributes to these developments by integrating these two approaches and applying them to three key elements of urban form: streets, plots and buildings. This contributes to a better understanding of each elements' respective characteristics (i.e., quantitative description of streets, plots and buildings using clustering), but in particular, , it offers insight into the patterns of alignment between the types (i.e., whether types are found in combination), which, to our knowledge, is novel especially at the scale of a comparative analysis across five European cities.

Finally, these results allowed us to create a link between quantitative analysis and theory by testing two well-known theoretical propositions in urban morphology: the concept of the burgage cycle (Conzen, 1960) and the theory of natural movement (Hillier, 1993).

In section 2, we describe the main methodological steps; in section 3, we present the results of the clustering analysis; section 4 discusses the frequencies of the observed combinations of types, or 'composite types', and discusses the findings in relation to the abovementioned theories in urban morphology; in the final section, we summarise the conclusions and discuss directions for future research.

2. Choice of urban form elements and development of types

2.1 Three central elements of urban form: streets, plots and buildings

In urban morphology, a distinction is often made between four key urban form elements: streets, street-blocks, plots and buildings (Conzen, 1960; Kropf, 2009; Moudon, 1994; Whitehand, 2001). Panerai et al. (2004) argue that the street-block is not a separate morphological component, but rather represents a group of plots bounded by the street network, while plots are the basic element in the pattern of land divisions and work as an organizational framework for human action and experience (Marcus, 2010; Whitehand, 2001). We follow this reasoning and will therefore not include the street-block as a separate element, but instead focus on streets, plots and buildings. These three urban form elements can be grouped into two distinct urban spaces: a continuous and publicly accessible space of streets, primarily used for movement, and a discontinuous space comprised of plots and buildings used for the generic function of long-term occupation (Hillier, 1996).

Two well-known theories in urban morphology address the relation between these components, each with its specific focus. Conzen (1960) introduced the concept of the burgage cycle, describing the evolution of built space over time, bounded by the spatial and legal framework of the plot. The burgage cycle concerns the progressive built occupation of plots, culminating in subdivision or amalgamation of original plots and a significant increase in built density (Whitehand, 2001). Hillier et al. (1993) discuss the pattern of alignment between configurational properties (i.e., street centrality), attractors (i.e., density and land use) and pedestrian movement in the theory of natural movement, in which the former drives the latter two. More central streets are thus associated with more populated streets with a higher density and diversity of land uses (ibid.). These two propositions will be tested by studying the patterns of alignment between plot and building types in the case of the burgage cycle and between street and building types in the case of natural movement.

2.2 Quantitative description of the elements of urban form

For the quantitative description of streets, we use the network centrality measure, angular betweenness, following the latest methodological developments in the field of space syntax (Hillier and Iida, 2005; Turner, 2007), which describes the number of times a street segment (i.e., a node) is part of the shortest paths between all other segments in the network, which has been proven to correlate well with movement flows and patterns (e.g., Hillier and Iida, 2005; Serra and Hillier, 2018).[1] The angular betweenness value of each street segment can be calculated considering the shortest paths between all streets in the network (i.e., global betweenness), or only considering those within a certain distance threshold around it, which can result in a large number of possible calculations. For instance, betweenness can be calculated at the scale that most people are willing to walk, approximately 500 meters walking distance (Gehl, 2010), but can also be calculated at any other scale that is regarded as relevant for the resaerch question at hand. To provide a continuous sampling of betweenness centrality, the calculation radii in this paper cover all radii between 500 meter walking distance and the full network. The chosen radii are equally spaced and have a small interval (i.e., 500m) in shorter distances up to 10km, a larger interval (i.e., 5km) from 10km up to 30km and finally an interval of 10km from 30km to 60km, resulting in a series of 27 radii. The identified typology of streets could, therefore, more accurately be referred to as a typology of multi-scalar angular betweenness centrality of streets but will be referred to in this paper as street types.

For the quantitative description of plots, we use three measures that capture the most essential properties of plots based on theory and studies in urban morphology (Cantarino and Netto, 2017; Marcus, 2000; Panerai et al., 2004; Siksna, 1998; Vialard, 2012): first, plot size, which captures the potential of plots to carry diverse users and owner strategies; second, plot frontage, which describes a plot's potential to link occupational space to movement space, measured through the proportion of the plot frontage that faces the street; third, plot compactness, which describes a plot's capacity to adapt to new buildings or land-use, measured by the degree of regularity of the shape of the plot (i.e., plot compactness). Because we are interested in how the morphological elements structure cities rather than the individual description of them, we use the cumulative opportunity measure[2], which measures the sum of opportunities that can be reached within a particular distance. For this paper, a distance is chosen that most people are willing to walk, commonly recognized to be approximately 500 meters (Gehl 2010). Thus, instead of plot size, the accessible number of plots within 500m is used. The identified typology of plots could, therefore, more accurately be referred to as the typology of plot patterns based on three morphological measures but will be referred to in this paper as plot types.

Through the addition of buildings, plots can be densified whereby more ´people and things´ can be stacked in the same location, both vertically, by adding more storeys, and horizontally, by covering more land with buildings; these can be measured with the floor space index (FSI) and ground space index (GSI), respectively. FSI is used to describe the total amount of built floor space in an area; GSI describes the division between built and non-built land in an area. Together, they also inform us about the average amount of building floors by dividing FSI by GSI. Berghauser Pont and Haupt (2010) have shown that by using FSI and GSI, a distinction can be made between different building types, which the variables separately were incapable of making (Steadman, 2013). This is in line with the work of Perez et al. (2018), but they added some shape measures that in the work of Berghauser Pont and Haupt (2010) could be detected with only FSI and GSI. Density is, like the plot measures, calculated using a cumulative opportunity measure; instead of measuring FSI and GSI for each plot or block separately, density is, thus, calculated for the area that can be reached within a 500 meter walking distance from each building. The identified typology of buildings could, therefore, more accurately be referred to as a typology of building fabrics based on two built density metrics, but will be referred to in this paper as building types.

See Table 1 for an overview of measures and the supplementary material for more details.

Element of urban form	Measure	Equation	Scale of analysis
Street	angular betweenness centrality	$B(x) = \Sigma_{s \neq x \neq t} (\sigma_{st}(x)/\sigma_{st})$	radius 500m - 60km
Building	accessible floor space index	AFSI(o) = AR(o,GFA) / Area(o)	radius 500m
	accessible ground space index	AGSI(o) = AR(o,BA) / Area(o)	radius 500m
Plot	accessible plots	AP(o) = AR(o,pc)	radius 500m
	accessible plot frontage	APF(o) = AR(o,sfl) / AR(o,ppl)	radius 500m
	accessible plot compactness	APC(o) = AR(o,pa) / AR(o,pba)	radius 500m

Table 1. Overview of elements of urban form and measures, equations and scales of analysis used in this paper; see supplementary material for more details.

2.3 Introduction of study areas

Five cities are included in the study: Amsterdam (the Netherlands), London (UK), Stockholm, Gothenburg and Eskilstuna (Sweden); see Table 2. Three main cities in Europe are selected for comparison in the study because, on the one hand, they carry certain socio-economic and historical similarities, while, on the other hand, they vary in their regional structure: Stockholm, a planned and dispersed finger-city, intertwined with green and blue wedges; London, a less planned city that has grown from the centre while absorbing many villages; and Amsterdam, the largest component in a semi-planned and dispersed poly-central conurbation.

In Sweden, two additional cities were included to allow for comparison of cities that have developed within the same institutional planning framework, but that differ in size. Together the five cities display a great variation in size and number of urban components. For reasons of comparability, the boundaries of the study areas are based on the Urban Morphological Zones (UMZ), defined by the European Environment Agency (EEA).[3]

City		Country	Area	Street length	Buildings	Plots	Addresses	Ratio		
				S	B	P	A	B / P	B / S	A / B
			sqkm	*km*	*no*	*no*	*no*			
ESK	Eskilstuna	Sweden	73	469	20 646	11 608	14 846	1.8	44	0.7
GOT	Gothenburg	Sweden	733	5 921	202 529	116 114	143 127	1.7	34	0.7
STO	Stockholm	Sweden	1 084	8 128	361 836	204 371	286 137	1.8	45	0.8
AMS	Amsterdam	Netherlands	417	4 930	365 992	229 576	464 587	1.6	74	1.3
LON	London	UK	3 411	36 650	4 721 997	2 719 125	6 232 500	1.7	129	1.3

Table 2. Basic quantities of the urban components in the five cities and some basic ratios: buildings per plot (B/P), buildings per street length (B/S) and addresses per building (A/S).

2.4 Methodology for comparison using cluster analysis and cross-tabulation

To develop types comparable across cities, similar geographic representation and measures of the three urban form elements are used as discussed in section 2.2 and all cities are classified simultaneously using k-means clustering analysis, well suited for large data sets. The main goal of clustering is to find similarities between objects to group them into classes: the greater the similarity (or homogeneity) within a class and the greater the difference between classes, the better (or more distinct) the clustering solution (Wilmink and Uytterschaut, 1984).

For street and plot types, unsupervised clustering (Tan et al., 2005) was used, which means that, besides the raw data and the number of clusters, no input is given to the algorithms.[4] Because the 27 angular betweenness centralities, measured at various scales, show multicollinearity and cluster analysis is sensitive to this, a principal component analysis (PCA) is conducted prior to clustering, following the method proposed in Serra (2013a; 2013b). This resulted in three principal components in each city, explaining between 94 to 97% of the total variance of the original variables. The PCA is used as input for clustering instead of the original 27 variables. For building types, a semi-supervised method was used (Fatehi and Asadi, 2017), where the initial number of clusters and cluster centroids are based on the findings of Berghauser Pont and Haupt (2010, pp 191).

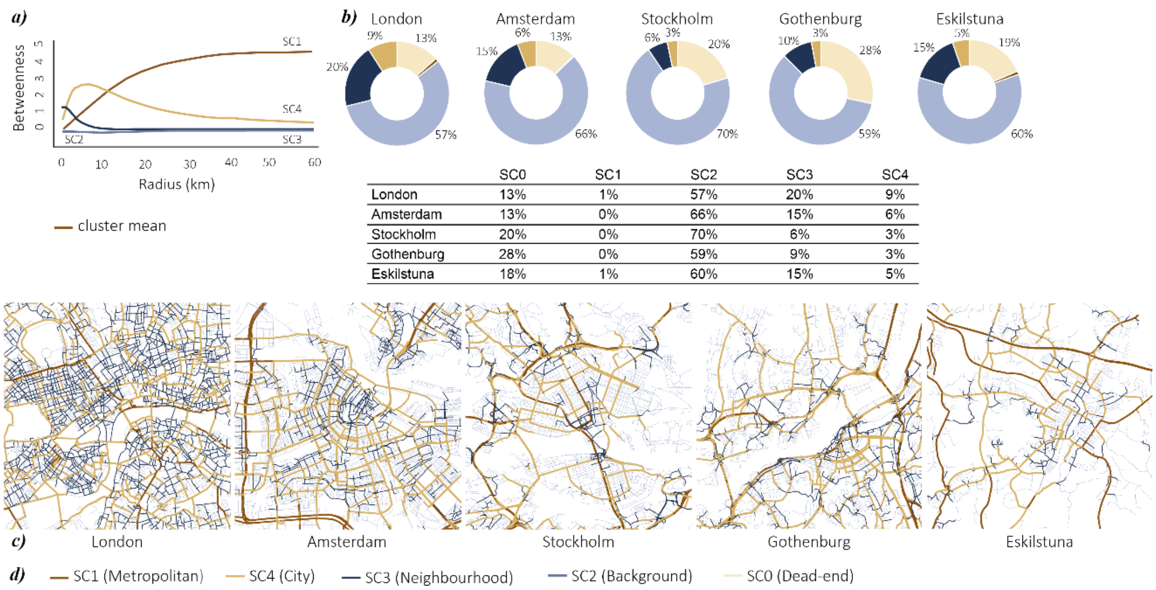
The purpose of the clustering is to identify natural structures in the data set.To know how well the proposed partition fits the input data, an evaluation method is needed, and the silhouette index has proven to achieve good overall results (Arbelaitz et al., 2012). This index is a normalized summation-type index where the cohesion is measured based on the distance between all the points in the same cluster and the separation is based on the nearest neighbour distance. Besides this, additional qualitative evaluation criterion were used to decide on the optimal number of clusters; for details, see the supplementary material.

After clustering, cross-tabulation is used to help find patterns between the types. To allow for this, the three elements of urban form were linked to each other using address points, since these are the real points of access from the street to the plot or building. Any streets, plots or buildings in the data set that are not associated with an address point were not included in the cross-tabulation analysis.

3. Spatial distribution and frequency of the street, plot and building types across the five cities

3.1 Street types

The cluster analysis resulted in five street types based on the silhouette plot analysis, which have the following profiles (Figure 1a): first, Background streets (street cluster 2 or SC2), representing the street segments with low betweenness values at all scales, which corresponds to what has been termed the ´background network´ in space syntax literature, in contrast to the ´foreground network´, which represents the streets with high centrality across scales (Hillier, 2009); next, Metropolitan streets (SC1), representing street segments with betweenness values that increase especially at the highest scales, typically capturing the highway network; third, Neighbourhood streets (SC3), representing street segments that have high betweenness at lower scales, but betweenness drops quickly at the higher scales; fourth, City streets (SC4), representing street segments that have consistently high betweenness values at most scales, but distinctly dropping values at the lowest and highest scales and, coming closest to what Hillier (2009) describes as foreground network; fifth, Dead-end streets (SC0), representing segments that have zero betweenness value at all scales, hence forming a very distinctive type. The typology described here shows strong similarities with the street types found for Porto in Serra (2013a) and proves that the method to generate the street types is reproducible and gives coherent results across cities.



	SC0	SC1	SC2	SC3	SC4
London	13%	1%	57%	20%	9%
Amsterdam	13%	0%	66%	15%	6%
Stockholm	20%	0%	70%	6%	3%
Gothenburg	28%	0%	59%	9%	3%
Eskilstuna	18%	1%	60%	15%	5%

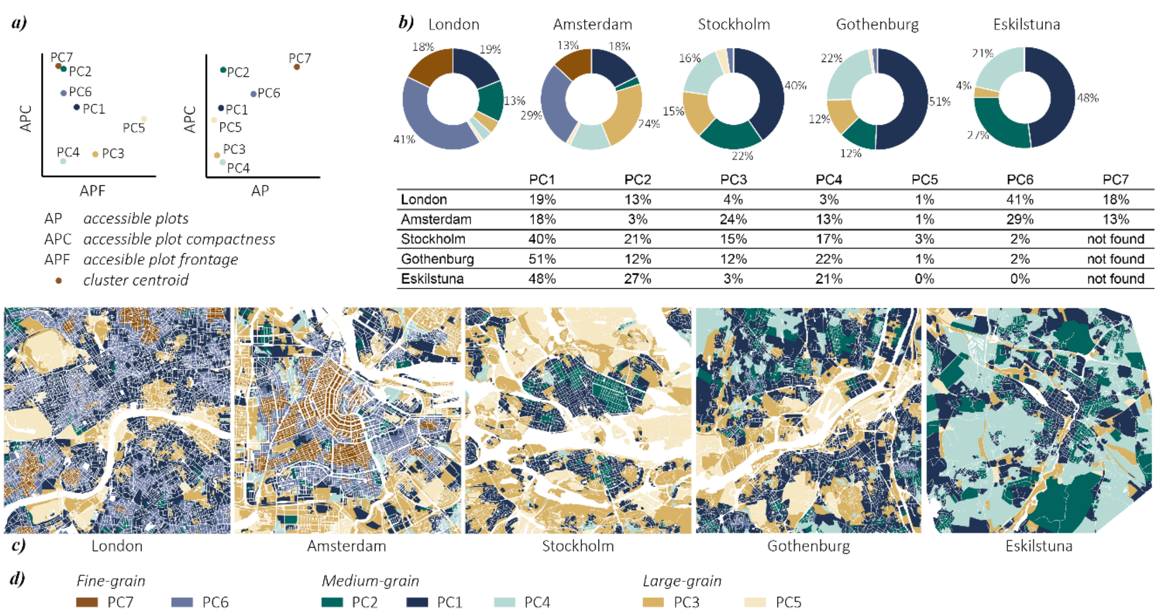
Figure 1. a) Scatter plot showing the centrality profiles of the street types with angular betweenness centrality on the y-axis (cluster mean) and the radii of analysis on the x-axis; b) Circle charts comparing the numerical distribution of street types in the five cities; c) Spatial distribution of street types in the five cities (for larger frames, see the supplementary material); d) key for a-c.

The numerical distribution (Figure 1b) shows very few streets of the Metropolitan type (SC1), while Background streets (SC2) dominate all cities, representing around two thirds of the streets (57%-70%) and confirms a well-known theoretical tenet of space syntax (Hillier, 2009). Besides these similarities among the cities, we can also observe some clear differences. Amsterdam and London have significantly fewer Dead-end streets (SC0) and more streets that we earlier described as forming the foreground network (SC3 and SC4) than the three Swedish cities. Moreover, the percentage of Neighbourhood and City Streets (SC3 and SC4) decreases in the Swedish cities when their size increases. In Eskilstuna, these two types represent 20% of all segments whereas in Stockholm they represent less than 10%. In Amsterdam and London, these two types represent 20-30%.

The spatial distribution (Figure 1c) reveals some generic patterns for the five cities, but also some distinct differences in the way that the cities are structured. The City street (SC4) structure in Amsterdam and London displays more of a regular grid pattern with cells/circuits, defining what could be called local areas. Within these local areas, Background streets (SC2) dominate, alternating with Neighbourhood streets (SC4) that could be described as the local main street, connecting two City streets that surround the local area. The Swedish cities, in contrast, present a more hierarchical tree-like structure of City streets (SC4), where Neighbourhood streets (SC3) function as loop routes that give access to Background streets (SC2) as well as to the many Dead-end streets (SC0). Summarising, we see clearly that Swedish cities are more similar to each other and distinct from Amsterdam and London.

3.2 Plot types

The clustering analysis resulted in seven plot types with the following profiles (Figure 2a): first, three plot types with medium sized plots (i.e. Medium-grain), but variation in the shape of the plots from compact (PC2) and medium-compact (PC1) to non-compact (PC4); next, the plot type Large-grain, non-compact (PC3) that shows similarities with PC4 in terms of the lack of compactness, but has lower accessibility to other plots (i.e., larger plot sizes) than PC4. The type Open plots (PC5) is different from the other plot types in all respects and represents plots facing streets on all sides, which means that the accessible plot frontage (APF) is almost 1. The last two plot types, PC6 and PC7, have high accessible plot (AP) values, implying that plots are relatively small. Besides this, PC6 and PC7 have a relatively low accessible plot frontage (APF) and a high accessible plot compactness (APC). They have this in common with two other plot types that, however, are much larger, i.e., higher AP values (PC1 and PC2).



	PC1	PC2	PC3	PC4	PC5	PC6	PC7
London	19%	13%	4%	3%	1%	41%	18%
Amsterdam	18%	3%	24%	13%	1%	29%	13%
Stockholm	40%	21%	15%	17%	3%	2%	not found
Gothenburg	51%	12%	12%	22%	1%	2%	not found
Eskilstuna	48%	27%	3%	21%	0%	0%	not found

Figure 2. a) Scatter plots showing the quantitative profiles of the plot types; b) Circle charts comparing the numerical distribution of street types in the five cities; c) Spatial distribution of street types in the five cities (for larger frames, see the supplementary material); d) key for a-c.

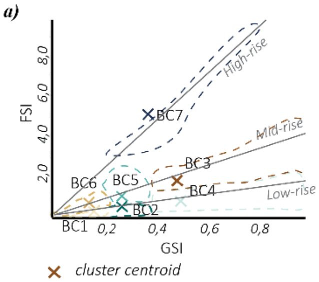
The numerical distribution of plot types (Figure 2b) reveals a striking difference between the Swedish cities, on the one hand, and Amsterdam and London, on the other hand. In Amsterdam and London, a high percentage of plots are compact and fine-grained (PC6 and PC7) that are either non-existing (PC7) or hardly present (PC6) in the Swedish cities. The absence of small plots in the Swedish cities might be explained by the fact that cities developed rather late and rationalisation of irregular city structures, including expropriation of land, was common practice (Ahlberg, 2005). In the Swedish cities, the Medium-grain, medium-compact plot type (PC1), instead, dominates.

The spatial distribution reveals some clear patterns in all the cities as well as clear differences between them (Figure 2c). Comparing the three Swedish cities, we can see that all historical cores are dominated by the medium-grain plot types PC1 and PC2. The zone of less compact plots in Stockholm immediately outside the core can also be seen in the other two Swedish cities. Amsterdam and London are very different from the Swedish cities, partly due to the dominance of the more fine-grained plot types. A comparison of these two cities shows an interesting difference, where in Amsterdam, the smallest and most compact plots (PC6 and PC7) dominate the core, while in London, these are found in clusters scattered throughout the whole city, maybe capturing the many villages absorbed while the city grew.

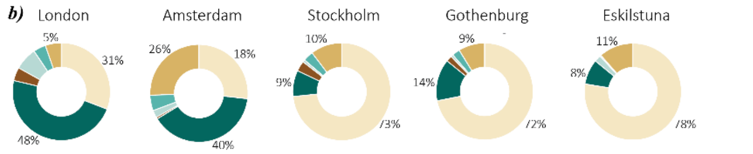
3.3 Building types

The clustering analysis resulted in seven building types that can be characterised by their mean accessible FSI and GSI values that at the same time inform us about the average amount of floors for each building type (Figure 3a). Three low-rise types are found with increasing GSI and FSI values: Spacious low-rise (BC1), with low FSI and GSI values and often describing villa areas; Compact low-rise (BC2), with medium GSI and FSI values; and Dense low-rise (BC4), where the GSI value is the highest of the three low-rise types. Note that the mean FSI of this low-rise type is almost similar to the mid-rise building type BC6. Next, we have three types where the average building heights are higher: Spacious mid-rise (BC6), with low GSI values and moderate FSI values (comparable to BC4); Compact mid-rise (BC5), with slightly higher FSI and GSI values; Dense mid-rise (BC3), with a combination of both high FSI and GSI values; and finally, Compact high-rise (BC7), a distinct type with very high FSI values and moderate to high GSI values.

a)



b)



	BC1	BC2	BC3	BC4	BC5	BC6	BC7
London	31%	48%	4%	7%	4%	5%	0%
Amsterdam	27%	39%	1%	2%	5%	26%	not found
Stockholm	73%	9%	3%	1%	3%	10%	not found
Gothenburg	72%	14%	2%	1%	3%	9%	not found
Eskilstuna	78%	8%	not found	2%	0%	11%	not found

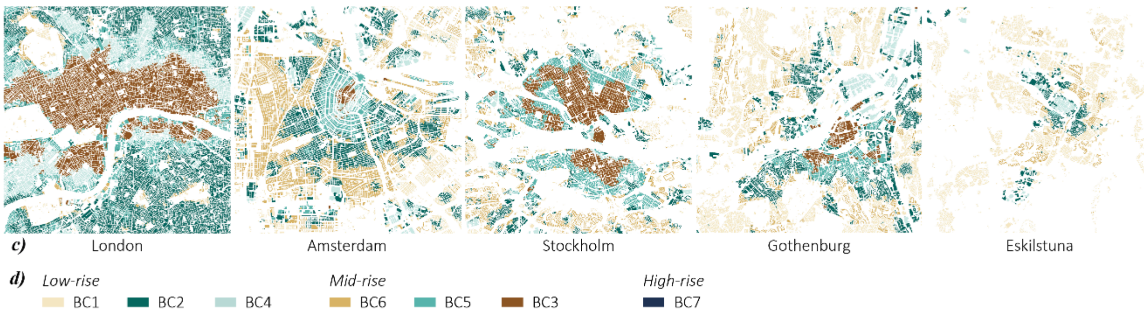


Figure 3. a) Scatter plot showing the density profiles of the building types with FSI on the y-axis and GSI on the x-axis; b) Circle charts comparing the numerical distribution of street types in the five cities; c) Spatial distribution of street types in the five cities (for larger frames, see the supplementary material); d) key for a-c.

The numerical distribution of these building types (Figure 3b) shows that the Spacious low-rise (BC1) building type dominates in the Swedish cities, while Compact low-rise (BC2) dominates Amsterdam and London. It is remarkable that these two low density types (BC1 and BC2) have such a high numerical share in all cities; together these two types occupy more than 80% of the plot area in all five cities, while the three most urban types, Compact mid-rise (BC5), Dense mid-rise (BC3) and Compact high-rise (BC7), together, use less than 3% of the land.

The spatial distribution follows a typical urban growth pattern in the form of rings radiating out from the historical core (Figure 3c). The densest and most compact building types are found in the historical cores of each city. In the second zone and along the main arteries, the building type Dense low-rise (BC4) is found. The third zone is dominated by the building type Compact mid-rise (BC5) that, in turn, is surrounded by the building type Compact low-rise (BC2). Then, a mix of Spacious mid-rise (BC6) and Spacious low-rise (BC1) follows.

All the cities follow this pattern more or less, but they also demonstrate some differences worth highlighting. Firstly, London has one building type that none of the other cities have: Compact high-rise (BC7). This type is found only in one location in London, Canary Wharf, one of the main financial centres of Europe containing a high concentration of tall buildings. Another difference is the dominance of the Compact low-rise type (BC2) in Amsterdam and London in comparison to the Swedish cities. Further, the Swedish cities show a rather strong contrast between the historical core, dominated by Compact and Dense mid-rise (BC5 and BC3), and the periphery, dominated by the most spacious building types (BC1 and BC6), while in London and Amsterdam an intermediate ring of intermediate density is found (type BC2). Furthermore, Eskilstuna completely lacks the Dense mid-rise type (BC3) and instead has a historical core dominated by the Dense low-rise type (BC4). One may argue that this has to do with the size of the city and the fact that it has not gone through a process of densification in the historical core, typical of larger cities.

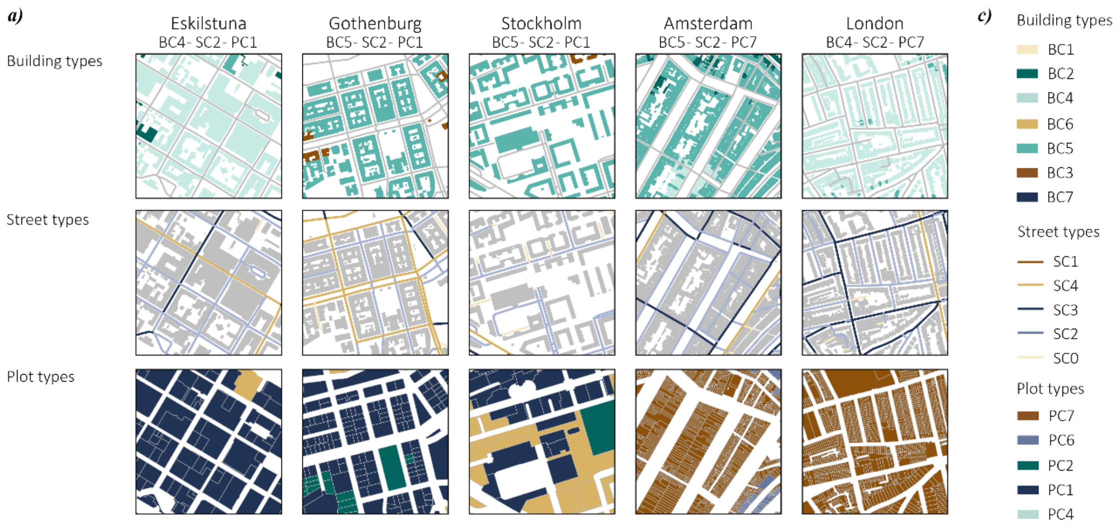
4. ´Composite types´ across the five cities

4.1 General comparison of composite types

Out of the 421 possible combinations of the three types (street type, plot type, building type), only 21 combinations are present in all cities, suggesting that these are generic types across the five cities. In other words, a large majority of the composite types do not appear, which is remarkable in some sense. The number of actual composite types found in each city were: Eskilstuna, 51; Gothenburg, 127; Stockholm, 153; Amsterdam, 181; London, 238.[5] In Eskilstuna, the smallest city, 41% of the composite types are the same as the 21 generic types across the five cities, while in London, the largest city, these types only represent 9%. This indicates an increase in diversity of composite types when city size increases.

The composite types show a dominance of the Background street type (SC2), relative to the amount of addresses in each building type, especially in the more spacious and low-rise building types (BC1, BC2 and BC6); see the supplementary material for an overview. The denser mid-rise building types (BC3 and BC5) have a more diverse representation of street types. Comparing the Swedish cities with Amsterdam and London, the varying dominance of plot types is most apparent, where the medium-grain types dominate the Swedish cities and the fine-grain plot types dominate Amsterdam and London. Only for the Spacious mid-rise building type (BC6), the patterns for all five cities are very similar with a dominance of plot type PC1 and PC3 in combination with the Background street type, SC2.

The most frequent composite type found in each city, relative to building type, is shown in Figure 4a. The medium-grain plot type PC1 dominates in the Swedish cities, while the fine-grain plot type PC7 dominates in the other two cities; the Background street type is most frequent in all cities. This pattern is repeated when looking at the dominating composite type in each building type and city separately (Figure 4b) and shows the same pattern as discussed earlier for the full cities (section 3). Worth mentioning is that in the examples shown in Figure 4a, Stockholm’s street types show less variation, while its plot types show more variation than in the other two Swedish cities. This might be caused by the large-scale reconstructions of parts of the older city in the nineteen sixties and eighties, where smaller plots were replaced with larger and more irregular ones, which further affected the continuity of the street pattern with repercussions on centrality, and thus, street type. Further, only in two cities and one building type did we find the Neighbourhood street type (SC3) being part of the most frequent composite type, namely in the densest mid-rise building type (BC3) in both Amsterdam and London. This is exactly what would be expected following the theory of natural movement, which we will discuss more extensively in the next section.



b)

BC1	BC1- SC2- PC1 : 26%	BC1- SC2- PC1 : 30%	BC1- SC2- PC1 : 30%	BC1- SC2- PC3 : 19%	BC1- SC2- PC6 : 28%
BC2	BC2- SC2- PC1 : 24%	BC2- SC2- PC1 : 31%	BC2- SC2- PC1 : 24%	BC2- SC2- PC6 : 27%	BC2- SC2- PC6 : 24%
BC3	not found	BC3- SC2- PC1 : 46%	BC3- SC2- PC1 : 36%	BC3- SC3- PC7 : 22%	BC3- SC3- PC1 : 23%
BC4	BC4- SC2- PC1 : 58%	BC4- SC2- PC1 : 30%	BC4- SC2- PC5 : 25%	BC4- SC2- PC6 : 20%	BC4- SC2- PC7 : 26%
BC5	not found	BC5- SC2- PC1 : 49%	BC5- SC2- PC1 : 32%	BC5- SC2- PC7 : 32%	BC5- SC2- PC1 : 17%
BC6	BC6- SC2- PC1 : 34%	BC6- SC2- PC1 : 32%	BC6- SC2- PC3 : 31%	BC6- SC2- PC3 : 27%	BC6- SC2- PC1 : 16%

Figure 4. a) Most frequent composite types for each city; b) Most frequent composite type for each building type and city (highlighted composite type corresponds to the maps shown in a; c) Key for a.

4.2 Testing the concept of the burgage cycle and the theory of natural movement

According to the concept of the burgage cycle (Conzen, 1960), the process of urbanisation results in plot subdivisions and densification and we, thus, expect to find, as a result of this process, fine-grain, compact plot types (PC1, PC2, PC6 and PC7) in combination with denser and more compact building types (BC3 and BC5). The opposite is also expected as Vialard and Carpenter (2015) have pointed out, meaning that large-grain plots of a more complex shape (PC3, PC4 and PC5) are expected to be more often combined with less dense and spacious building types (BC1, BC2 and BC6). Figure 5a shows the results of cross tabulation for plot and building types and confirms, at least in four out of five cities, that fine-grain, compact plots are more often found in association with denser building types. The share of fine-grain compact plot types increases from 60-75% in low dense areas to 70-95% in high dense areas. Only in the case of London is this pattern not confirmed, but there 91% of all plots are fine-grain and compact. Also the different cadastral system in London in comparison to the other cities (freehold and leasehold properties) can be the reason for this deviation.

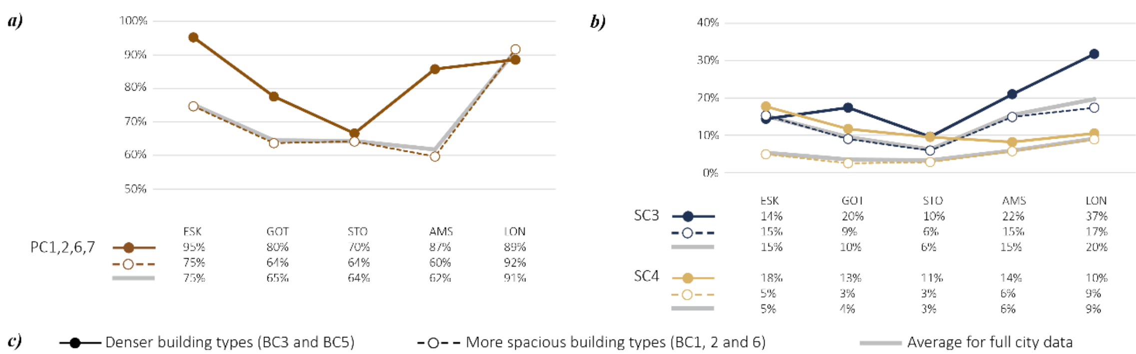


Figure 5. a) Line charts showing the distribution of fine-grain plot types in relation to building types, relative to the amount of addresses within that building type; b) Line charts showing the distribution of two street types in relation to building types, relative to the amount of addresses within that building type; c) key for a-b.

According to the theory of natural movement (Hillier, 1993), we expect the street types with high betweenness values across scales such as the Neighbourhood street type (SC3) and City street type (SC4) to be associated with denser building types (BC3 and BC5). The results of cross tabulation confirm this hypothesis in most cities, except for Eskilstuna, with a slightly higher share of the Neighbourhood street type in the lower dense building types (Figure 5b). Further, a difference between Neighbourhood and City streets in the different cities becomes apparent. In London, the City streets are almost equally often associated with low dense and high dense building types, while in the other cities and especially the Swedish cities, the differences between low and high dense building types are significant. For the Neighbourhood type streets, the trend is exactly the opposite, with large differentiation between low and high dense building types in London and Amsterdam and less so in the Swedish cities. This difference, we argue, is related to the earlier discussed spatial distribution and patterns of these types where the Swedish cities show a tree-like pattern and Amsterdam and London a more continuous grid-like pattern.

5. Conclusion and discussion

In this paper we have generated typologies of urban form for three key elements of urban form: street, plot and building, in five European cities. These types are a way forward to more precise descriptions of urban form that provide a richer vocabulary when describing street, plot and building patterns, which, in turn, could facilitate a more precise discussion about the future development of cities and about related normative guidelines.

For the quantitative description of the elements of urban form, we have used both geometric and configurational measures that contributed to an integrated spatial analysis, including multi-variable geometric descriptions and inter-scalar relational descriptions of urban form. Based on this approach, we contributed to a richer understanding of: first, the respective characteristics of the types; secondly, their spatial as well as numerical distribution within and across cities; and, thirdly, the patterns of combination between the types.

Summarising the differences between the five cities, we found great similarities among the Swedish cities, but we also found that Amsterdam and London are more similar to each other than either of them is with the Swedish cities. The Swedish cities lack the most fine-grained plot types (PC6 and PC7), dominant in Amsterdam and London, and have a much higher share of dead-end streets, a sign of their general strong hierarchical structure. Further, the Swedish cities show a rather strong rupture between the historical core and the periphery, while Amsterdam and London show a more continuous urban grading, especially when we look at the gradation of urban density.

We have also shown that the method presented can be used to create a link between quantitative analysis and theory, by testing two well-known theories in urban morphology: the concept of the burgage cycle and the theory of natural movement. The paper could partly confirm the burgage cycle theory with the results from the five cities; using only a cross-sectional analysis to validate a theory that, by essence, describes the evolution of plots and buildings over time, is, of course, not possible. Longitudinal studies are needed to analyse how plots and buildings evolved and would be an interesting next step in this endeavour to use quantitative spatial analysis to validate theories in urban morphology. For the theory of natural movement, we showed that street types with high betweenness values across scales are associated with denser building types, confirming the theory. However, ongoing studies relating these typologies to economic activities and pedestrian movement will allow for a more complete testing of the relation between configuration, attractors and movement patterns, central to the theory of natural movement.

Finally, an interesting next step to further develop the field of typo-morphology would be to use fuzzy or soft clustering where each observation belongs to a cluster to a certain degree, instead of hard clustering, used in this paper, where each observation belongs to a cluster or not. Fuzzy clustering is especially powerful in identifying, on the one hand, in-between types, where the degree of belonging is relatively low and equally shared by two or three clusters, and on the other hand, archetypes (i.e., the perfect example), where the degree of belonging is high.

Endnotes

1. The graph used is weighted by angular distance, meaning the angular deviation between two street segments, which is considered very influential to pedestrian movement, as observational data show that people tend to choose paths with the least angular deviation (e.g. Dalton, 2003).
2. Also known as the contour measure or isochrone measure (Bath et al., 2000).
3. To avoid potential boundary effects in the calculations of betweenness, the area actually analysed is 25km larger in all directions than the area studied.
4. From street segments, all cases with value 0 are excluded, because segments with value 0 are dead-end roads; for buildings, the value 0 represents areas without any buildings; both represent uniquely identifiable clusters that can be excluded from the statistical analysis.
5. It should be noted that for cross tabulation, we linked the different types through the address points; in case no address point is present, no composite type could be

defined. This has consequences, in particular, for areas without urbanisation where, for instance, a street and plot are present, but no building and thus no address is accounted for.

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