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The third dimension in urban geography: the urban-volume approach

Eric Koomen, Piet Rietveld
Department of Regional Economics, Faculty of Economics and Business Administration, Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV Amerdam, The Netherlands; e-mail: ekoomen@feweb.vu.nl, prietveld@feweb.vu.nl

Fernando Bacao
Instituto Superior de Estatística e Gestão de Informação, Universidade Nova de Lisboa, Campus de Campolide, 1070-312 Lisboa, Portugal; e-mail: bacao@isegi.unl.pt
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Abstract. A new methodology is presented that measures density in urban systems. By combining highly detailed height measurements with, amongst others, topographical data we are able to quantify urban volume. This new approach is demonstrated in two separate case studies that relate to the temporal and spatial dimension of the urban environment, respectively. In the first study the growth of the city of Amsterdam over the past century is studied. The urban-volume indicator is used to visualise and quantify the urban extension and intensification process. To critically analyse the spatiotemporal development of Amsterdam the self-organising-map approach is applied. Special attention is given to highlighting any signs of recent polynuclear development. The second case study compares the building-height frequency and spatial distribution of high-density zones in the four major Dutch cities. Additionally, the presence of built-up areas and the actual urban-volume values are explained simultaneously using a Heckman selection model.

Introduction

The urban landscape is changing continuously. Suburbanisation and urban sprawl have altered the classical monocentric city and given rise to new polycentric urban forms that have, for example, been described as edge cities (Garreau, 1991), network cities (Batten, 1995), corridors (Priemus, 2001), decentred cities (Stern and Marsh, 1997), and even edgeless cities (Lang and LeFurgy, 2003). It is important to note that different scale levels are considered in these studies on the polycentricity of urban form. These levels range from individual cities, through urban regions (Lambooy, 1998) to international macroregions (Dieleman and Faludi, 1998). This inconsistency in the scale levels applied obscures the ongoing debate on urban form. The discussion is further complicated by the fact that changes in the urban system are increasingly caused by the interdependency of different scale levels (Van der Laan, 1998). Central to all different descriptions of urban form, however, is the notion that the original city centres are losing their importance. Although the decline of traditional city centres in Europe does not nearly resemble the many North American examples, European cities also show a growing importance of subcentres (see, for example, Bontje and Burdack, 2005; Gaschet, 2002; Martori i Cañas and Suriñach i Caralt, 2002).

The Randstad area, the constellation of the four biggest cities in the western part of the Netherlands, is generally considered to be an interdependent network city (Batten, 1995; Van der Burg and Van Oort, 2001) in which the various urban subcentres are functionally related. Empirical evidence for this claim is, however, hard to find (Ritsema van Eck et al, 2006). The major Dutch cities, in fact, show signs of various opposing processes occurring simultaneously; inner-city redevelopment coincides with ongoing suburbanisation and, at the local scale, the intensification of urban functions is alternated with the demolition of high-rise apartment blocks to provide room for new single-family dwellings. All these processes lead to a continuous reshaping of the urban areas and, furthermore, influence the relationships with the surrounding suburban and rural areas. The formulation of effective spatial policies related to, for example, open-space preservation, mobility growth limitation and urban regeneration is hampered by a lack of knowledge of the relative importance of the forces that shape urban areas. A thorough understanding of current urban processes is a first step in drafting such policies.

Urban development often leads to changes in the intensity at which the already existing urban fabric is used and is thus difficult to trace with classical geographical analysis that typically focuses on lateral, two-dimensional urban extensions. Typical examples of this type of research compare two subsequent land-use maps and analyse the growth in urban areas, without studying changes in the intensity of urban land use (see, for example, EEA, 2006). This omission can, generally, be ascribed to the fact that land-use intensity is difficult to assess. Recent studies of urban density (for example, Batty et al, 2004; Longley and Mesev, 2002) have applied detailed individual address and postcode point-data to characterise intensities of land use. However, as Batty et al (2004) indicate, such approaches fail to incorporate the importance of the third (height) dimension in urban analysis. Without additional data (such as applied by Maat and Harts, 2001) these studies do not recognise the importance of tall or large, voluminous buildings that characterise high-density zones and that are extremely important in terms of their number of inhabitants, number of employees, or visual dominance. The analysis of the third dimension of urban morphology is scarce however, mainly due to limited data availability. Incidental examples reflect a painstaking data-collection process (see, for example, Frenkel, 2004; Holtier et al, 2000).

This paper presents the results of a detailed analysis of the third dimension of current Dutch cities that makes use of the recently released extremely detailed height information for the Netherlands. This new dataset allows for the relatively easy creation of an urban-volume layer that effectively captures urban morphology at the level of individual cities. Building volume is taken here as a proxy for urban density and, to our mind, offers the opportunity for the proper inclusion of the third dimension in studies of urban geography, as was previously advocated by Batty (2000). This approach has the advantage of closely resembling the human perception of urban density (Fisher-Gewirtzman et al, 2003) and its results are therefore easily interpreted. It should be noted here that high urban-density values do not necessarily imply the presence of high-rise buildings. This relation is more complex and depends on the density, ground coverage, and height of individual buildings as has been demonstrated by Berghauser Pont and Haupt (2007).

To demonstrate the potential of the newly developed urban-volume methodology for analysing urban form we apply it in two separate case studies that have a temporal and a spatial dimension, respectively. Time is the crucial element in the study that deals with historic development of urban density in the city of Amsterdam in the 1900–2000 period. An important element in the analysis of the temporal dimension is the application of the self-organising-map (SOM) method to help distinguish spatiotemporal relations in our rich datasets. The spatial dimension is the subject of a second application that compares and explains the building-height frequency and spatial distribution of high-density zones in the four major Dutch cities. Additionally, the presence of built-up areas and the actual urban-volume values are simultaneously explained with a Heckman selection model. In both case studies we seek evidence for polynuclear development at the level of major individual cities.

Urban-volume methodology

The urban-volume indicator that we apply in our analysis is based on a combination of height and topographic data. Figure 1 gives an overview of the methodology that was applied to come to an urban-volume layer. This section introduces the datasets that were used and discusses the most important steps in creating the urban-volume layer. A full account of the datasets and methodology that were used can be found in Koomen et al (2004) and Kaufholz (2004).

A crucial dataset in this analysis is the newly developed Dutch national elevation dataset (*Actueel Hoogtebestand Nederland* http://www.ahn.nl) that became available in 2003. This highly detailed dataset was collected over the preceding seven years under the supervision of the Survey Department and is based on laser-altimetric measurements. It has a height precision of about 15 cm standard deviation per point and an average point density of 1 point per 16 m^2 or better (Oude Elberink et al, 2003). These elevation data provided have enough spatial detail to distinguish individual houses and gives a detailed account of their heights. Huising and Gomes Pereira (1998) offer a full discussion of all possible errors relating to the laser system, the process of measuring the target surface. These errors range from 5 cm to 200 cm, but are for a large part corrected before the data are distributed. The remaining inaccuracy does not hamper our analysis, as we are interested in height differences of several metres. For this study we use a rasterised version of the original point-dataset with a 5 m $\times$ 5 m pixel resolution that provides an average value for all height points within the grid cell. For the rare cases that a grid cell is lacking information (for example, in the case of a missing overlap in the original data strips) a combination of mathematical techniques is used

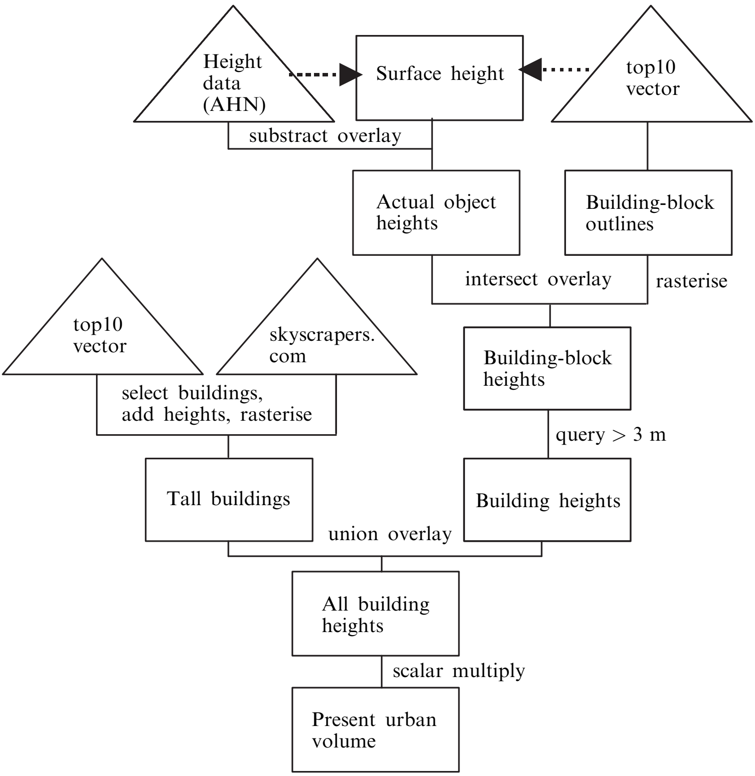

Figure 1. Cartographic model depicting the basic methodology for constructing the urban-volume layer. Note: AHN = *Actueel Hoogtebestand Nederland* (http://ww.ahn.nl); top10 vector see TDN (1998); skyscrapers.com see http://www.skyscrapers.com.

to fill in the gaps (Vosselman and Maas, 2001). Only the larger water bodies completely lack height information because of their reflecting characteristics. These do not pose a problem in our analysis because we are focusing on built-up areas.

To select only the heights of buildings an overlay is made with a thematic layer that contains detailed information on the topography [top10vector (see TDN, 1998)]. This layer allows for the distinction between residential and nonresidential building blocks and land that is not built-up. The latter is important to help reconstruct surface-level heights from the regional height dataset. By subtracting the surface height from the original heights that referred to the national datum level (0 m or mean sea level) we arrive at the actual building heights. In a second step the occasionally missing extremely high height values are added manually from an additional web source (http://skyscrapers.com). The grid-cell values are then multiplied by their surface area (25 m^2) in order to represent a volume-per-pixel of the buildings. This high resolution provides an extremely detailed, but also very heterogeneous and dispersed, account of urban volume. To allow for a more straightforward interpretation of the urban-volume indicator and, furthermore, speed up subsequent statistical analyses we chose to aggregate the urban-volume values to a 25 m $\times$ 25 m grid in which the total volume of the grid cells that make up these larger units is retained. By using this total aggregated value we preserve the underlying detailed observations based on the original topographical maps and height information. Small solitary buildings remain represented in the 25 m $\times$ 25 m grid; we lose only their exact position.

Spatiotemporal analysis of the Amsterdam urban volume 1900 – 2000

The capital of the Netherlands provides an especially interesting case-study area because its urban landscape has changed significantly in the past century. After almost two centuries of stagnation the city started to grow rapidly in the last part of the 19th century, reflecting a late catch-up with the industrial revolution. This growth period is still noticeable as an urbanisation ring around the historic centre. From the beginning of the 20th century urban expansion has been steered through municipal town planning, initially resulting in the addition of extensive new neighbourhoods, especially to the southern and western edges of town and the first major construction north of the central riverfront. After a disruption during WWII, extensive garden villages were added to the western and southern limits of town in the 1950 – 70 period, following the 1935 general extension plan (Van der Heiden and Wallagh, 1991). The latest major additions to the city layout can be found in the southeast, where a completely new neighbourhood for 100 000 inhabitants was constructed, and attached to the western and northern extremities of town. Large-scale inner-city redevelopment started in the 1980s and consists mainly of residential construction on the former maritime and industrial centre on the southeast shore of the riverfront. Compared with other major cities, Amsterdam was slow to start the construction of tall buildings (Kloos and De Maar, 1995). Since the 1980s, however, small concentrations of office building with maximum heights of up to 150 m have been constructed near the ring road at the western, southern, and southeastern parts of town and around a more centrally located railway station. Amsterdam is thus starting to show signs of polynuclear development. Our study aims at visualising and quantifying these urban changes by reconstructing the urban volume of the period 1900 – 2000.

The historic urban volume is reconstructed by combining the original urban-volume-data layer for the year 2000 with a detailed dataset that includes the year of construction of all individual buildings in the municipality of Amsterdam. The latter point dataset is combined with a detailed topographical dataset that contains building outlines. This enriched polygon map is then rasterised to allow for the recreation of the urban surface in any chosen time period. By selecting, for example, all cells that relate to buildings that were built in or before 1910 we arrive at a reasonable reconstruction of the historic urban area at that time. This reconstructed historic-urban-area map allows for the extraction of those grid cells in the urban-volume dataset that were supposedly built-up in or before 1910. This rough approach has, of course, some limitations. Old buildings may have been replaced by newer ones in the past 100 years, as the most recent construction year replaces any previous information on an edifice in our dataset. These locations will erroneously be left out of the 1910 analysis, introducing an underestimation of the urban volume in that time step. The opposite may also be true: the applied building-outline polygons describe urban blocks that are separated by streets or other open spaces. Especially in the old centre these areas may contain many individual buildings. As the date of the oldest building is assigned to the total block, recent volumes will be incorrectly related to older edifices, introducing an urban volume that might deviate from the original one. Visual inspection of the historic-urban-area map, however, shows the older central parts of town as more or less continuous surfaces with a relatively homogeneous volume distribution, indicating that the described limitations affect only isolated locations. Moreover, the reconstructed urban areas correspond well with other recreated land-use maps of the area based on historic data (see, for example, Knol et al, 2003). Since our analysis is mainly meant to explore the possible use of the urban-volume indicator we do not consider these drawbacks to be serious constraints to our analysis.

Historic urban-volume maps were created for every decade since 1900. A selection of the most crucial time steps is represented in figure 2. The figure highlights the above-average urban volumes per grid cell by classifying the volume values according to the standard deviations in the 2000 dataset. It shows the exceptionally high values in the darkest colours. The time series reflects the continuous growth of the city in all directions following the large-scale prewar (1940) and postwar (1970) extensions.

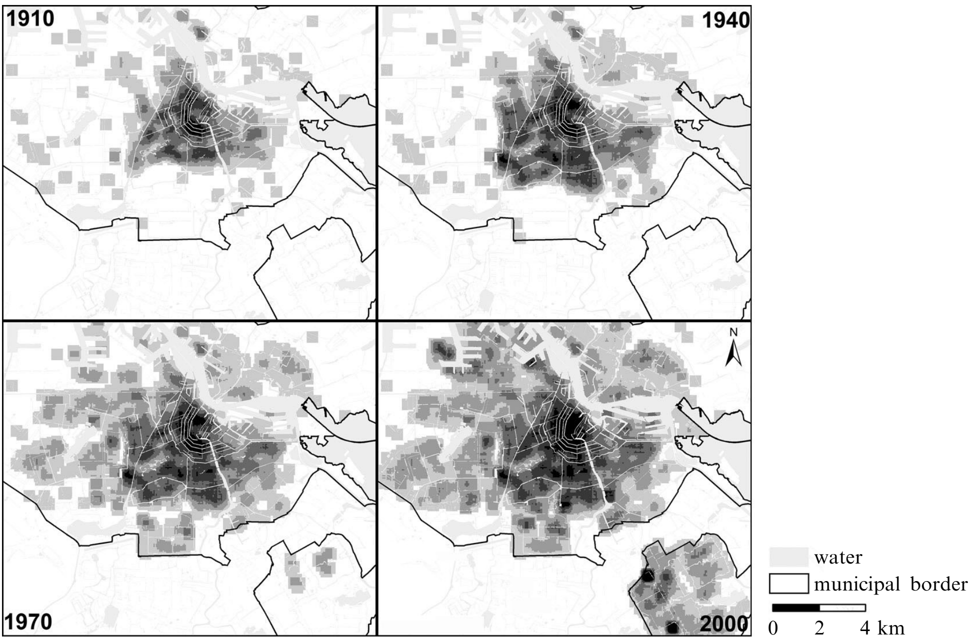

Figure 2. Reconstructed total urban volume ranging from low (grey) to high (black) in the city of Amsterdam for the years 1910, 1940, 1970, and 2000. For cartographic clarity the resolution was decreased to 50 m taking the total urban-volume values in a 500 m moving neighbourhood.

It furthermore highlights the recent, erratic spread of high-intensity zones throughout the city. The year 2000 urban-volume map shows an abundance of high-volume zones in almost all neighbourhoods of the city, clearly indicating a deviation from the original monocentric form. The presented reconstruction of urban growth in Amsterdam corresponds well to previous studies that qualitatively describe the two-dimensional growth in the past decades (for example, Dijkstra et al, 1999; Kahn and Van der Plas, 1999; Van der Cammen et al, 1988). Furthermore, the recently emerging polycentric development documented in our approach matches the observations of Bontje and Burdack (2005). Comparable studies looking specifically at urban-density changes in Amsterdam in the past decades using more traditional data sources would have provided interesting comparative material, but none was found. A rare exception is offered by a hybrid analysis for the relatively short period 1996 – 2002 that combines information on urban functions and residential, commercial, and employment density into a typology of urban environments (Maat et al, 2005). That study also indicates that the major Dutch cities show some polycentric development, but adds that central urban environments remain important and even increase in density. In addition, Maat et al (2005) recognise the development of polycentric urban regions consisting of many coalescing individual towns and cities.

Applying the SOMs approach

In order to analyse critically the obtained spatiotemporal patterns for the Amsterdam case study the SOM approach was applied. This can be described as a visualisation and analysis tool for high-dimensional data, but it is also applied for clustering (Bacao et al, 2005; Vesanto and Alhoniemi, 2000), dimensionality reduction, classification, sampling, vector quantisation, and data-mining (Kohonen, 2001). The fundamental idea of a SOM is to map the data patterns onto an n-dimensional grid of segments or units. This mapping tries to preserve topological relations, that is, patterns that are close in the input space will be mapped to segments that are close in the output space, and vice versa. Each segment, being an input-layer segment, has as many weights or coefficients as the input patterns, and can be regarded as a vector in the same space as the patterns.

For the Amsterdam case study a relatively large SOM with 60 segments was set up to isolate the areas of growth in volume with a certain degree of precision. Each input-data vector, a 25 m $\times$ 25 m grid cell, was composed of seven variables: the volume values for the years 1910, 1940, 1970, and 2000, and distances to the ring road, the nearest station, and the historic city centre. The use of these distances provides a geographic framework to the SOM analysis. In this way, each grid cell is not only considered by its volume values for the different years but also by its relative position in the city. The distances were, furthermore, included to explore whether the proximity of infrastructure and a central location do indeed relate to higher urban-volume values as was expected. They offer an indication of the potential relations that exist between location and urban-volume value, but do not quantify the strength of these relations as statistical regression analysis would do.

This analysis is included, however, to explore first the nature of these relations and assess whether a full-fledged statistical analysis is potentially useful. Table 1 gives an overview of the 23 SOM segments relating to urban development. The missing segments have an average urban volume of less than 1250 m^3 (equivalent to an average building-height of 2 m in the 25 m $\times$ 25 m cell) and are thus not considered to be important for our study. The segments characterise homogeneous groups of grid cells that share a common development history and relative location to key features of the city.

The SOM analysis clearly distinguishes the subsequent development phases and, furthermore, indicates some general location characteristics of the various groups of

Table 1. Selection of self-organising map analysis results relating to the historic development of Amsterdam; characteristic results are indicated in bold and are discussed in the text.

Segment number	Volume (m^3)				Distance (m)		
	2000	1970	1940	1910	to centre	to ring road	to nearest station
38	**1769**	118	2	1	4342	**699**	1034
50	**2114**	157	67	13	2156	2506	1531
29	**3064**	0	0	0	**7188**	2429	1336
30	**4449**	1	0	0	**9071**	4003	2019
35	**4922**	5	3	2	3489	1517	1619
36	**10213**	11	6	4	5013	1910	1408
42	**34249**	0	0	0	5901	2077	**862**
39	1533	**1528**	1	1	4361	**918**	**999**
34	2265	**2259**	25	20	6669	2955	2485
40	3017	**3011**	2	2	4250	**924**	1307
41	4650	**4639**	5	5	4387	1385	1424
47	7755	**7714**	1	0	4953	1560	1353
48	15223	**15187**	3	0	4704	1305	1477
45	1792	1785	**1784**	7	3149	1142	1263
51	2400	2368	**2365**	28	2262	2245	1338
46	3095	3093	**3093**	6	3009	1167	1230
52	4291	4288	**4288**	10	2785	1398	1268
53	6326	6321	**6321**	15	2410	1782	1333
54	15324	15324	**15324**	9	1832	2349	**900**
57	2326	2269	2263	**2229**	2266	2080	1457
58	3753	3739	3732	**3714**	1968	2197	1477
59	5629	5625	5622	**5618**	1727	2411	1513
60	10037	10034	10034	**10033**	**1459**	2740	1478

urban-volume values. The first seven rows for example refer to the last stage of urban development in the period 1970–2000. The low-density developments of segments 29 and 30 can be found far from the original city centre; these correspond with the recent construction of low-density single-family dwellings at the western extremities of town. The high-density developments near the stations of segment 42 represent the recent construction of extremely high office buildings. The 1940–70 period shows urban developments at 4 km to 7 km from the city centre. Several low-density developments (segments 39 and 40) are located near the ring road. The 1910–40 extensions can be found at an average distance of 2 km to 3 km from the centre, with the highest density near the stations (segment 54). The oldest parts of town are described in the last four segments, with the highest densities in segment 60 within 1.5 km of Dam Square where the city was founded.

Some of the most notable SOM segments are mapped in figure 3. This selection consists of the highest densities per building period, each reflecting the different characteristics of the relative high-rise developments in that period. The oldest developments (segment 60) only have a medium density but cover an extensive area. Isolated areas of higher density of the 1910–40 and 1940–70 period can be found within and outside the ring road, segments 54 and 48, respectively. By far the highest densities date back to the last building phase and are found near the stations (segment 42). Thus, the analysis indicates that certain high-volume values, on average, have specific locational characteristics without specifying the strength of these relations statistically. Later in this paper we will, therefore, analyse further the relative importance of the spatial factors included in the SOM for explaining the currently observed urban-volume patterns in Amsterdam and three other major cities.

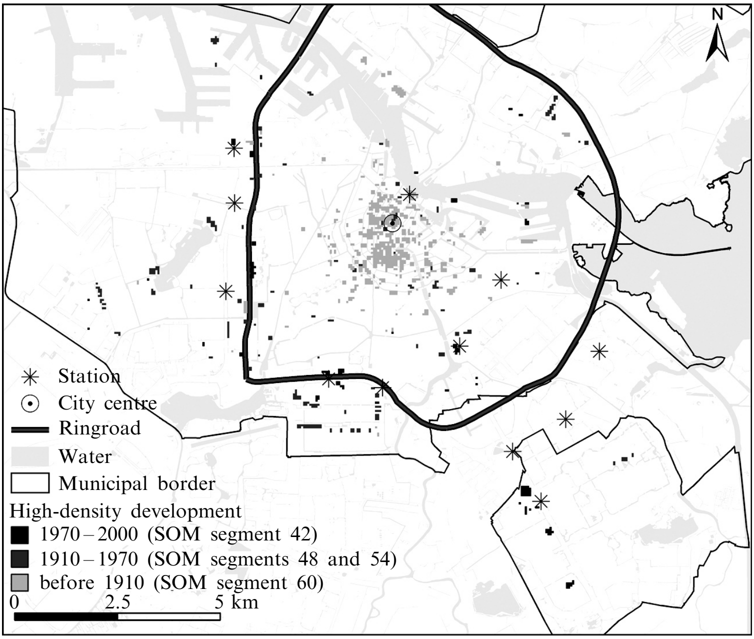

Figure 3. Selected self-organising map (SOM) segments reflecting high-density developments in different time periods. For cartographic clarity the grid cell resolution was decreased to 50 m.

Spatial comparison of the four major Dutch cities

The second case study in our analysis aims at comparing and explaining the urban density of the four largest Dutch cities: Amsterdam, Rotterdam, The Hague, and Utrecht. The urban-volume approach is used here to characterise the cities in terms of (1) their general appearance, (2) their building-height distribution, and (3) their spatial, urban-density patterns. After this characterisation we will make an attempt to explain the observed patterns.

The four selected cities are part of the metropolitan Randstad region in the west of the Netherlands, but differ in their history and layout. Amsterdam is the largest city in the country in terms of its number of inhabitants and has a large well-preserved historic centre. Rotterdam covers the largest surface area and has the largest built-up area, mainly as a result of its vast harbour area. Its centre was heavily bombed in WWII and it was almost completely rebuilt in the 1950s. The Hague is a relatively new city that houses the government, most ministerial buildings, and a large number of offices. Utrecht is the smallest of the four cities, both in terms of its population and its size. It is the only city that dates back to before 1000AD and it still retains buildings from its medieval history. Table 2 summarises the key statistics for the four selected cities derived from both the Dutch Central Bureau of Statistics (CBS, 2005) and our own urban-volume approach. The latter provides a more detailed account of the area that is actually covered by residential and nonresidential buildings than the generally used CBS built-up-area statistic that is based on detailed topographical maps that also contains land used for infrastructure and recreation and other building-related functions such as gardens and pavements. The buildings in all four cities cover less than a quarter of the total municipal land area. The Hague has the highest building-area density (22% of the municipal land surface), Amsterdam the lowest (12%). Interestingly enough, the population density per building area is highest in Amsterdam with close to 40 000 inhabitants per km^2 of building area. This more intensive use of space is also

Table 2. Key statistics for the four major Dutch cities. The built-up area includes all types of land use related to residential and nonresidential buildings, such as gardens and pavements. The building area only refers to the area actually covered by those buildings. Source: CBS (2005) for total population, land, and built-up area per municipality; other statistics are our calculations based on the methodology described in the text.

	Amsterdam	Rotterdam	The Hague	Utrecht
Land area (km^2)	165	209	68	61
Built-up area (km^2)	76	102	39	30
Building area (km^2)	19	26	15	9
Population	731 288	592 673	441 094	233 667
Population density per land area (persons/km^2)	4 429	2 841	6 494	3 804
Population density per building area (persons/km^2)	37 569	22 497	28 972	25 991
Urban volume (km^3)	0.216	0.299	0.162	0.092
Average building height (m)	11.1	11.4	10.6	10.2

indicated by the relatively high average building height in Amsterdam. Rotterdam is a special case, since many of its buildings are voluminous edifices related to commercial functions in the harbour. Its population density is therefore lower, but its average building height is higher than in the other cities.

Building-height frequency

In order to take a closer look at the base data at hand we first analyse the frequency distribution of the building-height dataset. By plotting the frequency of all observed building heights for all cities in one graph we can visually compare their full height ranges and related building-height distributions; see figure 4. Please note that the observations relate to the 5 m $\times$ 5 m pixels of the original dataset; thus, they are smaller than individual buildings. Height values have been truncated to full metres to facilitate faster calculation. This figure provides an initial characterisation of the three-dimensional appearance of the cities. In fact, the frequency distribution offers a unique three-dimensional fingerprint for

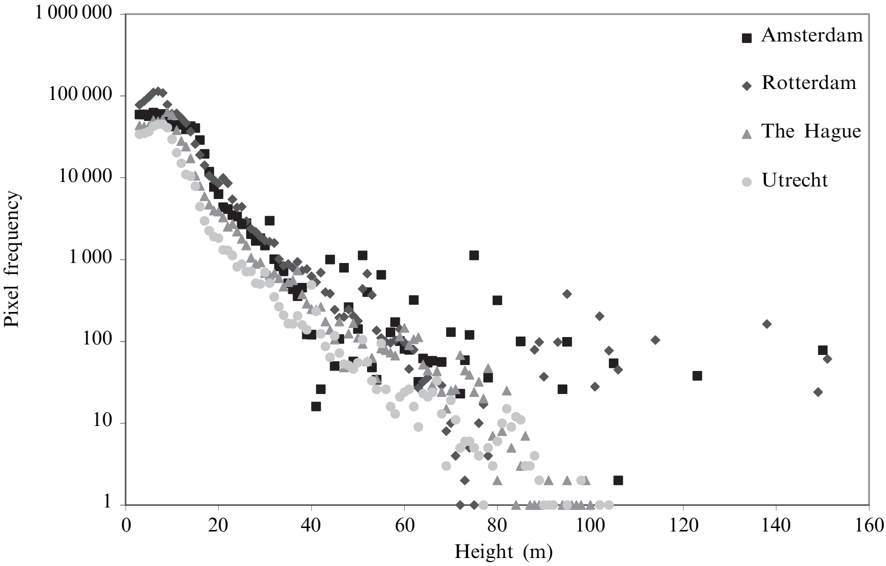

Figure 4. Building-height frequency distribution of the four major Dutch cities.

each city. Most striking about the height distribution for the four major cities is that they have the same basic shape. The most common building height is around 7 m – 9 m, indicating that single-storey and two-storey houses are less common than houses with three levels. Higher buildings occur less frequently with increasing height.(1) Only Amsterdam and Rotterdam have a considerable number of high buildings, as is shown in the somewhat erratic tail at the right-hand side. The maximum building heights are about 100 m for Utrecht and The Hague and about 150 m for Amsterdam and Rotterdam. The area below the dots represents the size of the cities in terms of their total building area. This indication is not straightforward in this case because of the logarithmic scale, but it is apparent that Rotterdam is the biggest city and Utrecht the smallest. The total urban volume can be inferred from the graph by multiplying the total number of observations for each height by their respective height value.

The observed building-height distributions closely follow the theoretical γ distribution as is expressed by the correlation (R_2) between the observed and fitted theoretical distribution that ranges from 0.95 to 0.99 for the four cities. The γ distribution is commonly applied to many different phenomena that have many occurrences with relatively low values and a long tail of ever scarcer high values as is the case with, for example, income distribution (Ferrero, 2004), rainfall frequency (Yoo et al, 2005), or flood frequency (Yue, 2001). It is comparable to the lognormal distribution that was used effectively by Batty (2001) to describe the rank – size population distributions in Great Britain in the past century. The fact that the building-height distributions for all four cities so closely follow the same mathematical description provides interesting opportunities for further research centred on a number of different research questions. Does this relation also hold true for smaller settlements and other countries? Is it consistent over time? And, perhaps more fundamentally, what processes govern these relatively strict relations? While conducting such research it is important to note, however, that the γ and related distributions may underestimate the mass at the extreme end of the height distribution and may need additional mathematical procedures to account for truncated data as is the case when certain very low values are discarded. See Victoria-Feser (2000) for more details on these issues.

A first attempt at pinpointing some of the relevant factors that explain high building densities is given later. First, however, we look more closely at the spatial patterns of the high-density areas.

Density patterns

To visualise the density patterns a filtering operation was applied on the original urban-volume layer. By aggregating the original 5 m resolution to a 250 m $\times$ 250 m grid using a maximum filter we are able to highlight the areas with highest densities. This approach puts a strong emphasis on the observed maximum values, which is in line with the visual dominance of tall buildings, but it overestimates their actual contribution to the total urban volume. Figure 5 shows the highest-density areas per city in black. These areas are defined here as having a maximum urban-volume value of 1250 m^3 (equivalent to a building height of 50 m in the original 5 m $\times$ 5 m grid). The resulting patterns are different for each city. Amsterdam and Rotterdam have the most high-density zones, but the highly erratic pattern of Amsterdam contrasts strongly with the conceptual pattern in Rotterdam. The Hague and Utrecht seem to have a more homogeneous spatial distribution of densities and offer less extremely

(1) The conspicuously low number of buildings with a height of approximately 40 m in Amsterdam is probably caused by the processing techniques of data suppliers. This inconsistency could, apparently, not be corrected fully by the manual addition of missing building heights. Apart from this, no other suspicious values were found.

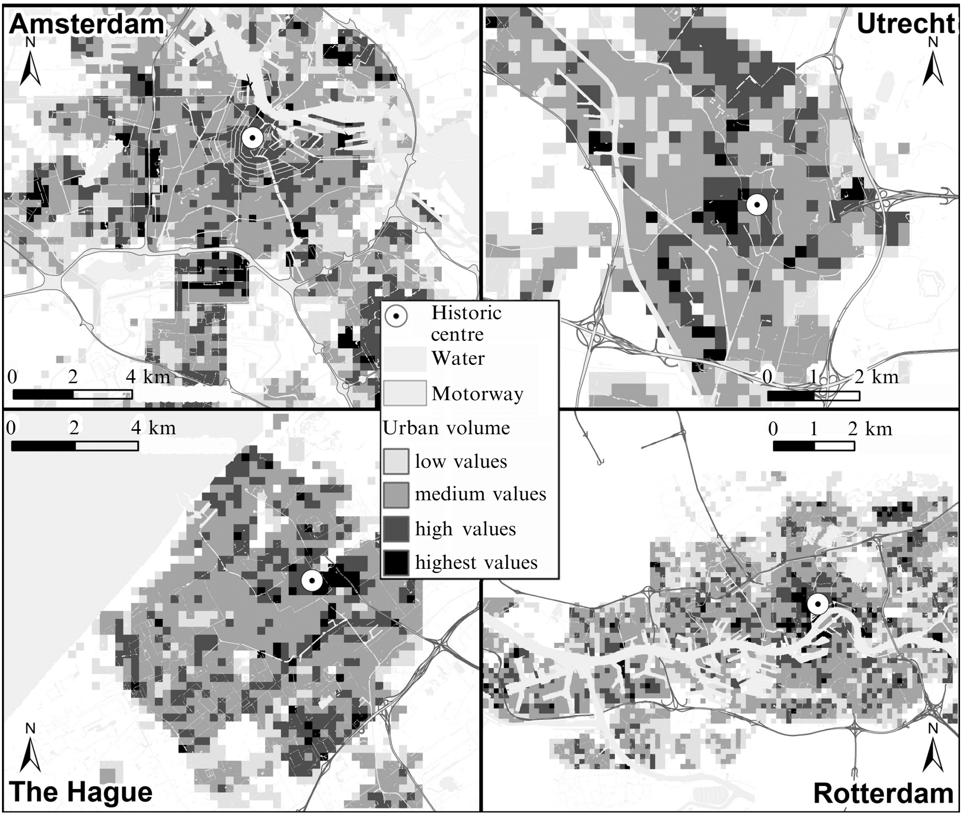

Figure 5. High-density patterns of the four major Dutch cities at 250 m × 250 m grid level. Scale varies per city.

high values. Both cities have a high-density area close to the traditional centre as well as several high-density areas outside that centre. Of the cities studied, only Rotterdam seems to be close to a classic monocentric city. Amsterdam offers by far the most varied cityscape.

Explaining urban density

After describing the observed urban-density distribution and patterns in the previous sections we now attempt to explain local-density values in a statistical analysis with a limited set of explanatory variables. We confine ourselves to such a limited set, as our main objective is to offer an initial indication of several important aspects that explain density patterns, rather than to explain this process fully. The analysis of urban density is done in two subsequent steps. First we analyse which factors explain whether a cell is classified as containing a building. In a second step we assess the importance of this same set of independent variables to explain the observed urban-volume values.

Since the analysis of urban volume is only possible for the locations where buildings exist, the two steps are related logically. Therefore, we chose to apply a Heckman sample selection model (Heckman, 1979) that simultaneously analyses the presence of buildings in a binomial logistic regression and the related urban volume in a linear regression (table 3). This type of analysis controls for possible correlations in the error term that might be present in the separately estimated models that are included in tables A1 and A2. The extent of this correlation is expressed in the ρ parameter. In the case of Utrecht and Rotterdam the values for this parameter differ significantly from zero, indicating that a correlation of the error terms is indeed present and thus underpinning the need for this approach. For the other two cities the more straightforward analysis with two separate statistical models would have sufficed. In fact, in all four cases the two approaches yield very similar results.

In this analysis we use a concise set of spatial explanatory variables related to the proximity of transport facilities and major spatial planning (zoning) regulations. The importance of the selected themes for explaining urban development is widely recognised. Relevant research pointing at their relevance for the Dutch context includes Koomen et al (2008), Rietveld and Bruinsma (1998), and Verburg et al (2004). The transport facilities chosen here are: local railway stations, intercity train stations, and motorway junctions. For each grid cell we calculated the distance to the nearest of each of these facilities. The negative impact of the proximity of transport infrastructure on urban development that might result from, for example, noise disturbance, is accounted for in two categorical variables that indicate the presence of a railway or motorway area within 500 m. The remaining spatial variables are also categorical and indicate, where appropriate, a location within a noncentral part of town when it is divided by a natural barrier (major river), or a location within a restrictive-development zone related to either open-space preservation (buffer zone) or the noise contour of the national airport. For operational reasons we incorporate proximity here as a Euclidean distance to the nearest facility. We thus refrain from using more elaborate measures that, for example, take actual travel time or perceived distances into account, mainly because we are looking at relatively short distances within major urban areas with intricate infrastructure systems. It should, furthermore, be added that from our analyses we exclude the locations that refer directly to water, motorway, or railway areas, since these are, by our definition, not built-up.

The results from the part of the analysis that explains whether or not one or more building cells of $5\ \text{m} \times 5\ \text{m}$ are present in a $25\ \text{m} \times 25\ \text{m}$ grid environment are included in the bottom half of table 3. The explanatory power of the estimated statistical model cannot readily be assessed, but the R^2 values of the related separate binomial logistic model ranging from 0.28 to 0.35 indicate a reasonable fit (appendix, table A1). The impact of the explanatory variables is, in general, according to expectation: an increase in distance to local railway stations, intercity train stations and, to a lesser extent, motorway junctions leads to a decrease in the probability that a cell is built-up. The proximity of a motorway or railway positively influences the probability of built-up areas. A location in a restrictive-development zone (buffer zone) or the noise contour around the national airport is also less likely to be built-up. Some exceptions to the general pattern can be observed that are probably caused by specific local conditions. In Amsterdam and The Hague the distance to motorway junctions has a small positive impact. This may be caused by the fact that the motorways here are located relatively far from the main built-up areas. In The Hague this situation may be partly caused by the city's location at the coast, which forms a natural barrier to the construction of a ring-road type of road infrastructure. The positive impact of the proximity of a railway in Rotterdam can possibly be attributed to the presence of extensive industrial areas surrounding the cargo railway line in the vast harbour area of the city. The fact that this harbour area and related working-class districts are situated on the southern (noncentral) shore of the river Rhine possibly explains why this shore is more likely to contain built-up areas. In Amsterdam the northern (noncentral) shore of the river IJ has very few facilities as is reflected in the negative impact of a location here. The relatively low impact of the proximity of intercity train stations in Amsterdam and Rotterdam may be related to the very fine spatial detail of the analysis. The applied datasets clearly show the main (central) stations to be

Table 3. Heckman selection model for explaining urban volume and presence of built-up areas. All variables are significant at the 0.01 level, unless indicated otherwise.

	Coefficient (SE)			
	Amsterdam	Utrecht	The Hague	Rotterdam
Ln urban volume				
N	88 256	39 340	64 952	129 490
Constant	7.550 (0.024)	7.506 (0.024)	7.408 (0.016)	7.081 (0.019)
Distance (km) to nearest:				
local train station	−0.018 (0.006)	0.005** (0.006)	0.027 (0.006)	−0.099 (0.004)
intercity train station	−0.209 (0.005)	−0.150 (0.007)	−0.239 (0.008)	−0.038 (0.002)
motorway junction	0.202 (0.006)	−0.065 (0.008)	0.133 (0.008)	0.103 (0.003)
Location within:				
500 m of a motorway	−0.013** (0.014)	0.041* (0.018)	0.040* (0.017)	−0.052 (0.012)
500 m of a railway	−0.034* (0.016)	0.082 (0.012)	−0.016** (0.012)	0.257 (0.007)
a buffer zone	−0.787 (0.058)	−1.980 (0.164)	−1.096 (0.095)	−1.706 (0.189)
Amsterdam North/ Rotterdam South	−0.552 (0.039)			0.106 (0.013)
airport noise contour	−0.647 (0.015)			
Built-up area indicator				
N	288 079	117 490	177 786	503 443
Constant	0.582 (0.010)	1.580 (0.020)	0.746 (0.009)	0.333 (0.005)
Distance (km) to nearest:				
local train station	−0.152 (0.002)	−0.167 (0.004)	−0.204 (0.004)	−0.146 (0.002)
intercity train station	−0.115 (0.003)	−0.352 (0.003)	−0.320 (0.003)	−0.067 (0.001)
motorway function	0.085 (0.004)	−0.087 (0.006)	0.272 (0.003)	−0.041 (0.001)
Location within:				
500 m of a motorway	−0.272 (0.008)	−0.555 (0.010)	−0.356 (0.013)	−0.345 (0.006)
500 m of a railway	−0.432 (0.007)	−0.067 (0.010)	−0.119 (0.011)	0.021 (0.005)
a buffer zone	−1.366 (0.013)	−1.990 (0.052)	−2.337 (0.026)	−2.261 (0.050)
Amsterdam North/ Rotterdam South	−1.020 (0.010)			0.450 (0.006)
airport noise contour	−0.029 (0.010)			
ρ	−0.002 (0.043)	0.169 (0.024)	0.020 (0.034)	0.069 (0.029)
σ	1.098 (0.003)	1.054 (0.005)	0.998 (0.003)	1.124 (0.003)
λ	−0.002 (0.047)	−0.178 (0.026)	0.020 (0.034)	0.077 (0.033)
log likelihood	−279 480	−115 668	−183 762	−444 872

* Significant at 0.05 level; ** not significant at 0.05 level.

surrounded by sizeable non-built-up areas that are usually made up of public squares and clusters of local infrastructure. Initial attempts to include the distance to the (historic) centres of the four cities produced more ambiguous results, as these sites are normally located close to the (main) intercity station thus leading to collinearity problems. Borzacchiello et al (2007) provide a related analysis on the maximum distances of the accessibility impacts on urban development in the same four cities described here. Their work also contains a more extensive description of the data preparation and statistical-analysis process.

The upper part of table 3 shows the results for the part of the model that explains the local urban-volume values. These values show a comparable impact of the individual explanatory variables as in the explanation of the presence of buildings. The model, however, only explains a limited part of the variance in urban-volume values as is indicated by the low R^2 values of the related separate linear-regression model explaining urban volume (appendix, table A2). This relatively poor performance is probably related to the limited variability in the urban-volume values as was also apparent in the building-height frequency (figure 4). The vast majority of the buildings are of a similar height (around 10 m) and high-rise buildings are scarce. The analysis does, however, indicate a number of factors that favour the presence of high, voluminous, or closely packed buildings. In particular, the proximity of an intercity train station positively influences high volume values. Apparently a location near a main (central) station is crucial for high urban densities. In the case of Amsterdam and Rotterdam the presence of regular train stations seems to matter too, albeit to a lesser extent. The proximity of a motorway junction has an opposite impact: an increasing distance is likely to lead to higher volume values. In Rotterdam a strong positive effect is generated by the proximity of the railway itself. These findings contradict the common suggestion that high-rise buildings are generally to be found at the edges of cities near motorways. In this respect, Dutch cities apparently differ from their North American counterparts, which do show a preference for high-density developments at their edges (Garreau, 1991; Stern and Marsh, 1997). This will be related to the fact that the Dutch railway network, as opposed to the North American ones, is one of the most dense and heavily used systems in the world (Korver et al, 1993). Accessibility by car, on the other hand, is known to be much more important in the North American situation (Orfeuil and Bovy, 1993). The observed continuing importance of the current (historic) city centres is very much in line with the empirical and simulated evidence presented by Batty (2001). Frenkel (2004) also reports that existing high-rise buildings in the Tel Aviv metropolitan region in Israel have a higher probability of occurring in the core city. On the other hand, in his research he found that proposed high-rise buildings have a higher probability of occurrence in the outer rings of the region.

Conclusion and discussion

The proposed urban-volume indicator provides an adequate characterisation of the actual physical appearance of a city in time and space. What is more, the quantitative description allows for an objective, highly detailed statistical analysis of urban patterns. Thus, the indicator helps in visualising and quantifying the impact of the different forces that shape our cities. In this respect it provides useful input to the ongoing debate on urban (re)development.

The presented spatiotemporal analysis of the urban development of the city of Amsterdam combines the urban-volume indicator with other equally detailed base data. This study provides an interesting insight into the making of the city. The gradual, lateral extension is clearly mapped, but the analysis also shows the growing importance of numerous high-density zones throughout the city. This finding is further quantified in the related SOM analysis. The SOM results also indicate the addition of isolated high-density zones to the historic medium-density city centre in the last century. Furthermore, this approach proves the recent emergence of small but extreme high-density developments near stations at a considerable distance from the centre.

The urban-volume indicator is also useful for characterising the differences in urban density in the four major Dutch cities. This study shows a distinction between cities in which high-density areas are concentrated in the original city centres (Rotterdam and The Hague) and cities that show these areas at a considerable distance from the centre (Amsterdam and Utrecht). The distribution of the high-density zones in the latter cities clearly suggests a polycentric appearance. Thus, the layout of the major Dutch cities reflects evidence of opposing centripetal and centrifugal forces. The urban-volume indicator can help visualise and quantify the impact of these forces, thus providing useful input to the ongoing debate on urban (re)development. Compared with current topographical maps the indicator can also be used to provide a more exact delineation of the part of an urban area that is actually covered with buildings. This is helpful, for example, in hydrological studies that focus on water management in cities.

The statistical analysis that explained the presence of urban areas and their urban-volume value puts less emphasis on the extremely high volume values and indicates the importance of intercity and local railway stations in urban development. The distance to motorway junctions was found to be less important in this respect, indicating that the urban system in these major cities is still concentrated in the traditional centre served by railway infrastructure. Local zoning regulations may be another important factor in explaining high-volume values. The four cities studied have different regulations with respect to high-rise developments and each city has appointed specific zones where such developments are favoured or restricted (Klerks, 2002; Susebeek, 2005). Restrictions do, for example, apply to part of the historical centres of Amsterdam and Utrecht. This aspect could not be included in the statistical analysis because of the lack of appropriate data, but may very well account for part of the observed differences between the cities.

An interesting extension to this research would be the inclusion of additional information on different types of urban land use. This would allow for a distinction in, for example, residential, commercial, and industrial areas and could help disentangle the factors that shape the expected density differences between these types of use. Another especially valuable addition to the current approach is offered by the incorporation of high-resolution data sources that represent building-use intensity. Such detailed information on the number of residents or employees per building is still very difficult to obtain, but would enhance the current representation of urban density. The potential of this enhancement is demonstrated, for example, by the work of Anas et al (1998) and Riguelle et al (2007) on employment densities in Los Angeles and Belgium, respectively.

In more general terms, the analysis presented shows the enormous potential of the highly detailed spatial datasets that are currently becoming available in many countries. This is not only true for the high-resolution height data that were used in this paper, but also for other data derived from sources such as the newest generation of remote-sensing satellites, large-scale inventories of cadastral institutes, and the tracking and tracing of mobile-phone users. The latter type of data can be used, for example, in the (real-time) monitoring of traffic flows based on the movements of individuals. For many other socioeconomic phenomena we are now able to use fine-grained data that allows spatial analysis at scales that were unimaginable until recently. From the current analysis it becomes clear that such highly detailed datasets offer considerable challenges in terms of both visualisation and analysis of fine-scale developments over extensive areas. The increasing level of detail of newly available data sources, in fact, calls for a rethinking of current analysis and presentation methods, leaving many new research routes open for explanation.

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Appendix

Table A1. Binomial logistic regression explaining the presence of built-up areas. All variables are significant at the 0.01 level unless indicated otherwise.

	Coefficient (SE)			
	Amsterdam	Utrecht	The Hague	Rotterdam
Constant	−1.790 (0.024)	−0.126* (0.083)	−1.621 (0.037)	−2.506 (0.080)
Distance (km) to nearest:				
local train station	−0.243 (0.004)	−0.271 (0.007)	−0.383 (0.007)	−0.270 (0.002)
intercity train station	−0.198 (0.004)	−0.588 (0.006)	−0.531 (0.005)	−0.132 (0.001)
motorway junction	0.135 (0.006)	−0.131 (0.011)	0.504 (0.006)	−0.097 (0.002)
Location within:				
500 m of a motorway	−0.462 (0.013)	−0.927 (0.017)	−0.552 (0.020)	−0.641 (0.009)
500 m of a railway	−0.701 (0.011)	−0.105 (0.017)	−0.321 (0.018)	0.320 (0.008)
a buffer zone	−2.565 (0.027)	−4.404 (0.152)	−4.628 (0.070)	−6.217 (0.158)
Amsterdam North/ Rotterdam South	−0.062 (0.016)			0.917 (0.009)
airport noise contour	−1.734 (0.019)			
N	288 079	117 490	188 585	872 266
Adjusted R^2	0.275	0.345	0.335	0.308

* Not significant at 0.05 level.

Table A2. Linear regression explaining urban volume of built-up areas. All variables are significant at the 0.01 level, unless indicated otherwise.

	Coefficient (SE)			
	Amsterdam	Utrecht	The Hague	Rotterdam
Constant	7.550 (0.014)	7.477 (0.024)	7.415 (0.011)	7.122 (0.007)
Distance (km) to nearest:				
local train station	−0.019 (0.004)	0.024 (0.006)	0.029 (0.005)	−0.091 (0.002)
intercity train station	−0.209 (0.004)	−0.110 (0.004)	−0.235 (0.004)	−0.034 (0.001)
motorway junction	0.202 (0.006)	−0.058 (0.008)	0.129 (0.004)	0.106 (0.002)
Location within:				
500 m of a motorway	−0.014* (0.011)	−0.110 (0.015)	0.044 (0.016)	−0.032 (0.009)
500 m of a railway	−0.034 (0.009)	0.091 (0.012)	−0.014* (0.012)	0.256 (0.007)
a buffer zone	−0.789 (0.029)	−1.672 (0.158)	−1.058 (0.070)	−1.555 (0.178)
Amsterdam North/ Rotterdam South	−0.647 (0.015)			0.082 (0.008)
airport noise contour	−0.554 (0.018)			
N	88 256	39 340	64 952	129 490
Adjusted R^2	0.133	0.027	0.065	0.051

* Not significant at 0.05 level.