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The impact of urban proximity, transport accessibility and policy on urban growth: A longitudinal analysis over five decades

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Abstract
Transport accessibility is assumed to be a main driver of urbanisation. Like many other metropolitan regions, the Randstad, the population and economic core of the Netherlands has experienced significant urbanisation, transport network expansion and spatial policies aimed to channel urban growth. This paper investigates the long-term relationships between the development of railway and motorway networks, urbanisation, and spatial policies, by using a panel dataset consisting of grid cells measured at six time points from 1960 to 2010. Generalised Estimating Equations analysis was applied to model the built-up area. Predictors include proximity to and accessibility by transport infrastructure, vicinity of urban areas, and spatial policies. Results indicate that road and rail accessibility alike, stably influenced urbanisation, but less than proximity to urban areas. Spatial policies played a significant role in channelling new urbanisation, while preserving the centrally located green and mainly rural area. Remarkably, the legacy of earlier policies is still significant despite shifts in predominant Dutch spatial policies. The findings are expected to be relevant for comparable poly-nuclear areas.

Keywords
Urbanisation, transport accessibility, spatial policies, Randstad, generalised estimating equations

Introduction

The magnitude, determinants, rate and the spatial distribution of urban growth or urbanisation are major concerns for policy makers. Accessibility, neighbourhood interactions and spatial policies are argued to be the most influential factors on

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contemporary land use change (Verburg et al., 2004). Transport infrastructure is believed to stimulate and guide urban growth via the improvement of accessibility (Anas et al., 1998). This assumption is demonstrated in a long tradition of policies aiming at channelling urban growth by investing in transport infrastructure. It is also known that urbanisation is more likely to happen near existing urban areas, examples being the concentric development of cities or the appearance of suburbs nearby major cities. Furthermore, where urbanisation occurs or not, is related to spatial planning and policies which designate areas for, or preserve locations from development. Examples are planning clustered urbanisation and restricting development in certain greenfield areas to reduce urban sprawl as implemented in Dutch spatial policies during the 1970s and early 1980s (Dieleman and Wegener, 2004).

Change in land use patterns such as urbanisation is a slow process with a low reversibility (Wegener and Fürst, 1999). Thus, it can only be studied over the long term. However, only few empirical studies investigate this process over multiple decades. Most studies investigating the long-term impact of transport infrastructures model population change as a proxy for growth and urbanisation (e.g. Baum-Snow, 2007; Duranton and Turner, 2012; Koopmans et al., 2012; Levinson, 2008). Rail networks have influenced the distribution of population and encouraged a rise in urban population especially after their emergence, although with variations across regions and time periods (Atack et al., 2010; Mojica and Marti-Henneberg, 2011). They have also facilitated suburban population growth (Garcia-Lopez, 2012; Levinson, 2008). Similarly, road networks, specifically motorways, have attracted population to their vicinity (Baum-Snow, 2007; Duranton and Turner, 2012; Garcia-Lopez, 2012).

Fewer long-term studies directly model the share of accessibility to rail and road networks in land-cover change. They generally conclude that access to road networks, especially motorways, increases the likelihood of conversion to urban land (Hu and Lo, 2007; Iacono and Levinson, 2009; Levinson and Chen, 2005; Muller et al., 2010). The role of railways in the conversion to urban land is less evident as both positive, negative and neutral impacts are reported (see for a detailed overview Kasraian et al., 2016).

Land use change does not occur in isolation, and is more likely to happen close to already urban areas. Thus, neighbouring land uses play a significant role (Cervero and Landis, 1997; Iacono and Levinson, 2009). The influence of existing urban areas is shown to be a significant driver of conversion to urban land (Arai and Akiyama, 2004; Cheng and Masser, 2003; Luo and Wei, 2009).

From the few studies which have investigated specific policies (Verburg et al., 2004), the majority has reported their role as significant. Examples are the effect of the introduction of land markets on determining the type and location of land development (Wu and Yeh, 1997), the attraction of employment by designated New Towns (Padeiro, 2013) and the positive relation between the amount of land in the urban fringe not subject to municipal planning regulations and urban sprawl (Burchfield et al., 2006).

Based on existing literature, the following gaps are addressed. First, most long-term studies on the role of transport infrastructures, model urban change through population densities. From a spatial perspective, it is useful to measure the amount of urbanisation as the area converted from undeveloped to urban land, and the dynamics of its spatial distribution in the long run. Second, several studies directly model land-cover change, but suffer from one or a combination of the following limitations: their time spans rarely exceed two decades; only the final decades of the 20th-century are investigated; the focus is on the road network only; the study area is limited to a single city-region. Third, empirical studies quantifying the long-term impact of spatial policies are scarce.

This study builds on previous research by examining the spatial distribution of urban areas over a longer time period, a larger urban region including a conurbation of several cities and

investigating the impact of both road and rail networks, urban proximity as well as spatial policies. We assume that urbanisation is a process partly driven by transport accessibility, partly by the attraction of existing urban areas, and partly by policies aimed at influencing autonomous processes. Thus, this study investigates three assumptions. First, the proximity to rail and road infrastructure and their provided access to centres of activity encourage urbanisation. The influence of the road network however is expected to be stronger than the rail network, as the road network is larger, more fine-grained and has a higher share in the number of travelled trips. Second, existing urban area encourages further urbanisation, and large conurbations exert a stronger attraction than smaller ones. Third, urbanisation is not only an autonomous process driven by transport accessibility and attraction of existing urban area but also a process which is simultaneously influenced by spatial policies. To test these assumptions, the main research question this paper addresses is: to what extent have transport accessibility and proximity to existing urban areas affected the spatial dynamics of urbanisation in the Randstad, and to what extend do spatial policies influence this? As we study this over 50 years, we examine to what extent the effects of these determinants vary over time.

This study models urbanisation in the Greater Randstad Area from 1960 to 2010. It is, however, not only interesting for Dutch planners, as urban containment and densification strategies have been applied in many regions of the world over the past decades.

Research design

Study area

The Randstad is the population and economic core of the Netherlands situated in its west and including the four major cities of Amsterdam, The Hague, Rotterdam and Utrecht (Figure 1). It is a useful case study, first because it is a polycentric urban region with a variety of development types including metropolitan areas, medium-sized and small cities and rural areas. Second, it has experienced a dynamic period of changes in land use and transport infrastructure networks. Since the 1960s, after decades of decline, the railway network's development stabilised. It has extended since the 1970s with new stations and new types of light rails. Motorways were introduced in the 1960s and significantly expanded to cover the country in the following decades. Third, this period has witnessed the application of various national transport and spatial policies to curb urban sprawl. The Concentrated Deconcentration of urban development and the designation of Growth Centres were implemented during the 1970s and early 1980s. These policies aimed to channel the suburbanisation which started in the 1950s and increased drastically between mid-1960s and the end of 1970s. Furthermore, they aimed to preserve the Green Heart, a mainly rural area at the centre of the Randstad (Dieleman and Wegener, 2004). During the 1980s, the revival of inner cities was encouraged under the Compact City agenda (Maat et al., 2005). In the 1990s and within the Compact City agenda, the focus was placed on channelling new urban (re)development to brownfield locations within the existing urban areas, and new greenfield locations on the edges of existing cities – the so-called Vinex locations. During the same time – and contrary to the car dominated transport policies of the 1960s and the 1970s – sustainable transport and public transport were promoted (Annema and van Wee, 2009). In the 2000s, the concept of Network Cities was introduced, focusing on the definition of a network of cities connected by transport network corridors (Alpkokin, 2012). While these events are partly specific to the Netherlands, the general trends – such as the massive post WWII suburbanisation, the initial focus on the development of the road network which was later changed to the public transport or both, and an array of spatial policies to curb urban sprawl – could be witnessed in many (at least western) countries.

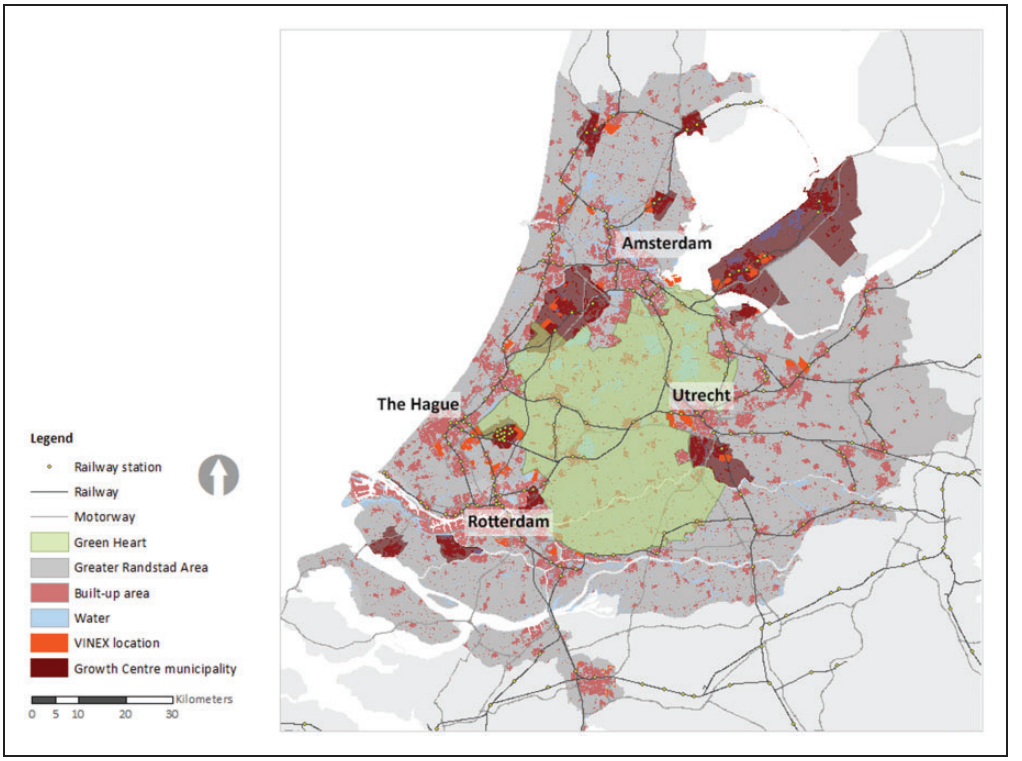

Figure 1. The Greater Randstad Area in 2010.

Data

Urbanisation is defined in this paper as the conversion of non-urban to urban land. Urban land is the physical space used for urban functions (including real estate for housing, services, companies, infrastructure and parks) which we generally refer to as the built-up area. Urbanisation is measured as changes in the proportion of built-up area in 500 m by 500 m grid cells. Transport accessibility and urban proximity are chosen as determinants of urbanisation based on existing literature and because they are related to both the autonomous process of urbanisation as well as the Dutch spatial policies applied in the past decades. Transport accessibility is addressed from a location- and infrastructure-based viewpoint, measured by distance to transport nodes and travel times on the transport networks. Urban proximity is measured as the amount of urban land and the size of the largest urban agglomeration in a cell's vicinity. The investigated policies are the Dutch physical planning concepts and their spatial representations since 1960.

The study period is 1960–2010 and includes six time points, referred to as decades: 1960, 1970, 1980, 1990, 2000, and 2010. Data for the built-up area for 1960 to 1990 is derived from the Historical Land Use Maps of the Netherlands (HGN), developed by Alterra, University of Wageningen, originally with a raster resolution of 25 m by 25 m. The source for the built-up area of 2000 and 2010 is the "adjusted version" of the Land Use Dataset (Mutatiereeks Bodemgebruik 1996–2010), created by Statistics Netherlands (CBS) and The Netherlands' Cadastre, Land Registry and Mapping Agency (Kadaster). The measurements of the

built-up area from HGN and Mutatiereeks datasets are not fully comparable, as the first shows the *existing* land cover, while the latter demonstrates the land use type. However, after inspection, we believe this difference will not substantially affect the outcomes since it is equally spread across the study area.

Units of analysis are 37,891 cells of 500 m by 500 m. Measured at six time points, they construct a balanced panel (i.e. including the same number of observations for each subject) with 227,346 observations. The original 25 m by 25 m HGN cells were aggregated to reduce spurious accuracy and processing time. The investigated transport networks are rail (light/heavy rail), and road (motorways and regional roads). To mitigate edge effects (Turner, 2007), transport networks exceeding the study area with 10 km were used to calculate transport accessibility indicators. The rail network was derived from the National Railways dataset (Nationaal Georegister, 2011) and by eliminating the as-yet-undeveloped railway lines and stations for earlier time points. Historical road networks, the boundaries of Vinex developments, the Green Heart and Growth Centres municipalities were provided by the Environmental Assessment Agency (PBL).

Variable specification

The dependent variable is the urbanised proportion of cell i at decade t (U_i^t). The assumptions that transport accessibility, urban proximity and spatial policies influence urbanisation are translated into six hypotheses. According to these hypotheses, a cell's likelihood to become urbanised increases if one or more of the following conditions are met.

1. It is located in the vicinity of access points to transport infrastructure. This is measured by the Euclidian distance to the nearest railway station and motorway exit.

$$S_i^t \stackrel{\text{def}}{=} d_{i,st}^t \tag{1}$$

where S_i^t is railway distance of cell i at time t, measured as Euclidean distance d between cell i and the nearest railway station st.

$$E_i^t \stackrel{\text{def}}{=} d_{i,ex}^t \tag{2}$$

where E_i^t is motorway distance of cell i at time t, measured as Euclidean distance d between cell i and the nearest motorway exit ex.

2. It is close or adjacent to existing urban areas. The urban proximity which captures the so-called "neighbourhood effect" is measured by the amount of urban land in a cell's vicinity.

$$P_i^t = \sum_j a_j^t, \quad j \in [1, n] | d_{i,j}^t \leq r \tag{3}$$

where P_i^t is the urban area existing in the neighbourhood of cell i at time t, a_j^t is the urban area of the neighbour cell j (from 1 to n) at time t and $d_{i,j}^t$ is the distance between cell i and its neighbour cell j at time t which is less than or equal to an r radius of 1.5 km.

3. It is close or adjacent to large existing urban areas (urban agglomerations), and the larger the size of the urban agglomeration in a cell's vicinity, the larger its urbanisation likelihood. For instance, of two cells with the same amount of urban land in their neighbourhood, the one near a big city is more likely to urbanise than the one near a

village. This is measured as the size of the largest urban agglomeration within a 1.5 km radius of a cell.

$$G_i^t = \max_k \left(v_k^t\right) | v_k^t \cap_{i,r}^C \neq \emptyset \tag{4}$$

G_i^t is the large urban area existing in the proximity of cell i at time t, $\max_k(v_k^t)$ is the area of the largest urban area (from 1 to k) within a C circle neighbourhood of cell i with an r radius of 1.5 km.

4. It is located close to a centre of activity, where there is a concentration of jobs and amenities. The most prominent of such concentrations in the Randstad are the so-called "Big Four" which include the cities of Amsterdam, The Hague, Rotterdam and Utrecht. The Big Four are represented by act, with $q = 4$.

$$F_i^t = \min_{act}(rail_{i,act}^t), \quad act \in [1, q] \tag{5}$$

$$rail_{i,act}^t = to\_rail_{i,st}^t + on\_rail_{st,act}^t \tag{6}$$

where F_i^t is minimum railway travel time of cell i at time t to an activity centre by the railway network, $\min_{act}(rail_{i,act}^t)$ is the travel time between cell i and the nearest activity centre act by the railway network at time t. $rail_{i,act}^t$ is the travel time between cell i and an activity centre act by the railway network at time t. $to\_rail_{i,st}^t$ is the time needed to cover the shortest Euclidian distance between cell i and its nearest railway station st, assuming a speed of 15 km/hr. $on\_rail_{st,act}^t$, is the time needed to cover the distance between the station st that is nearest to cell i and the activity centre act (proxied by the central stations of Amsterdam, Utrecht, Rotterdam and The Hague Hollands Spoor station), with an assumed speed of 70 km/hr.

$$H_i^t = \min_{act}(road_{i,act}^t), \quad act \in [1, q] \tag{7}$$

$$road_{i,act}^t = to\_road_{i,ra}^t + on\_road_{ra,act}^t \tag{8}$$

where H_i^t is minimum road travel time of cell i at time t to an activity centre by the road network, $\min_{act}(road_{i,act}^t)$ is the travel time between cell i and the nearest activity centre act by the road network at time t. $road_{i,act}^t$ is the travel time between cell i and an activity centre act by the road network at time t. $to\_road_{i,ra}^t$ is the time needed to cover the shortest Euclidian distance between cell i and the road access point ra (i.e. any point on a regional road or motorway exit), assuming a speed of 15 km/hr. $on\_road_{ra,act}^t$ is the time needed to cover the distance between the road access point ra and the activity centre act (proxied by the road access point that is nearest to central stations of Amsterdam, Utrecht, Rotterdam and The Hague Hollands Spoor station), with assumed speeds of 50 km/hr and 100 km/hr for regional roads and motorways respectively.

5. It is at a location where multiple activity centres could easily be accessed using the transport networks. In other words, areas which can reach various activity centres in a shorter time are more likely to become urbanised. Examples are a city like Delft (close to both Rotterdam and The Hague) or cities in the central Green Heart like Gouda which have relatively fast access to all of the Big Four, represented by act, with $q = 4$.

This is measured by the *sum* of travel times (as explained above) to the Big Four by the road and rail network calculated as:

$$W_i^t = \sum_{act} rail_{i,act}^t, \quad act \in [1, q] \tag{9}$$

where W_i^t is the sum of travel times for cell i at time t by the railway network, and $rail_{i,act}^t$ is the travel time between cell i and activity centre act by the railway network at time t.

$$Z_i^t = \sum_{act} road_{i,act}^t, \quad act \in [1, q] \tag{10}$$

where Z_i^t is the sum of travel times for cell i at time t by the road network, and $road_{i,act}^t$ is the travel time between cell i and activity centre act by the road network at time t.

6. It is planned for development and is not preserved by policy. This is measured by dummy variables indicating whether a cell belongs to designated Growth Centres, Vinex locations or the Green Heart.

The above hypotheses are operationalised into eleven indicators: *distance to nearest train station/motorway exit* [km] (hypothesis 1); *urban land in a cell's 1.5 km circle neighbourhood* [sq. km] (hypothesis 2); *largest urban agglomeration in a cell's 1.5 km circle neighbourhood* [sq. km] (hypothesis 3); *travel time to the nearest Big Four by the rail/road network* [hour] (hypothesis 4); *sum of travel times to the Big Four by the rail/road network* [hour] (hypothesis 5); and dummies for *Growth Centre municipality*, *Vinex location* and the *Green Heart* (hypothesis 6).

Model specification

The dependent variable U_i^t is the urbanised proportion of cell i at time t, where t refers to each of the six decades. The model takes into account the longitudinal nature of the data: the observations are related over time, so they are not independent. Furthermore, it accommodates the bounded nature of the response variable, namely the *share* of the built-up area in a cell, which ranges from zero to one.

Generalised estimating equations (GEE) analysis was chosen, an alternative being the random effects (RE) method. The choice of GEE-analysis was based on the relevance of its findings for policy makers as the drawn inferences are population-averaged (Allison, 2009; Gardiner et al., 2009). GEE-analysis can also estimate fractional response variables for balanced panels (Papke and Wooldrige, 2008). It imposes a "working" correlation structure between dependent observations and uses quasi-likelihood estimation. The simplest dependence between observations is *exchangeable* which assumes equal-correlation for within-subject observations, regardless of the time interval (Twisk, 2012). Matrix 11 shows the exchangeable correlation structure for the observations of a subject at three time points, where the correlation between time points are the same and equal to ρ:

$$\begin{array}{c} \\ t_1 \\ t_2 \\ t_3 \end{array} \begin{array}{c} \begin{array}{ccc} t_1 & t_2 & t_3 \end{array} \\ \begin{bmatrix} - & \rho & \rho \\ \rho & - & \rho \\ \rho & \rho & - \end{bmatrix} \end{array} \tag{11}$$

Various correlation structures can be assumed between a subject's observations, however, imposing more complicated correlation structures increases the number of degrees of freedom due to the estimation of more correlation coefficients. The goal is to find the most simple correlation structure with the fewest degrees of freedom and the best fit for the data (Twisk, 2012).

Twisk (2004) provides equation (12) for GEE-analysis of a longitudinal dataset with a dichotomous outcome. This model could be applied to a proportional variable (which is the case here), as it is possible to easily transform logit with a fractional outcome to a weighted logistic regression with dichotomous outcomes with the same parameter estimates and statistical inferences (Liu and Xin, 2014). The model was estimated using the *xtgee* command (Stata 14). The distribution of the dependent variable belongs to the logit family, the link function is binomial and the assigned correlation structure is exchangeable.

$$\text{logit}\left(U_i^t\right) = \beta_0 + \beta_1^t + \beta_{2l}\sum_{l=1}^{L} X_{il}^t + \beta_{3m}\sum_{m=1}^{M} X_{im} + corr_i^t + \epsilon_i^t \tag{12}$$

where:
U_i^t = urbanised proportion of cell i at time t,
β_0 = intercept,
β_1^t = coefficient for time,
β_{2l} = coefficient for time-dependent predictor variable l,
X_{il}^t = time-dependent predictor variable l for cell i at time t,
L = number of time-dependent predictor variables,
β_{3m} = coefficient for time-independent predictor variable m,
X_{im} = time-independent predictor variable m for cell i,
M = number of time-independent predictor variables,
$corr_i^t$ = working correlation structure, and
$\in_i^t$ = error for cell i at time t.

In this case, the time-dependent predictors are transport accessibility and urban proximity. While policies did change over time, they are considered time-independent. For instance, a cell in a Vinex development is dummy-coded as Vinex for all time points while this policy was only introduced in the mid-1990s. This allows us to trace the influence of Vinex policy on a cell's proportion of urban land before and after this policy was introduced.

Results

Descriptive statistics

Table 1 describes the time-dependent variables for each decade. The statistics show that urbanisation, as the amount of built-up area (1) and consequently the fraction of built-up area (2) grows over time in a cell. This is also evident in Figure 2 which represents Randstad's urbanisation over the study period. The averages for distance of grid cells to railway stations (a) and motorway exits (d), the travel time to the nearest Big Four (b, e) and the sum of travel times to the Big Four (c, f) by both road and rail decrease over time. However changes in road accessibility values are more drastic than the rail accessibility values. The reason is that the railway network has been rather stable while the motorway network has undergone major developments over the study period. Trends of urban proximity indicators (f, g) show that as time goes by and urbanisation continues, the

Table 1. Descriptive statistics of variables over the study period.

	1960	1970	1980	1990	2000	2010
(1) Built-up area in a 500 m by 500 m cell [sq. km]						
Mean	0.02	0.03	0.04	0.04	0.04	0.05
Std. Deviation	0.04	0.05	0.06	0.06	0.07	0.07
(2) Fraction of built-up area in a cell						
Mean	0.09	0.12	0.14	0.15	0.18	0.19
Std. Deviation	0.17	0.21	0.23	0.25	0.28	0.29
Independent variables						
(a) Distance to nearest railway station [km]						
Mean	6.53	6.43	6.18	5.53	5.43	5.37
Std. Deviation	4.91	4.94	4.92	4.22	4.22	4.23
(b) Travel time to the nearest Big Four by the rail network [hour]						
Mean	0.81	0.80	0.79	0.74	0.73	0.73
Std. Deviation	0.41	0.42	0.42	0.37	0.38	0.38
(c) Sum of travel times to the Big Four by the rail network [hour]						
Mean	5.00	4.95	4.91	4.71	4.68	4.66
Std. Deviation	1.71	1.73	1.75	1.57	1.59	1.59
(d) Distance to nearest motorway exit [km]						
Mean	13.92	6.40	4.98	3.88	3.79	3.78
Std. Deviation	11.15	5.37	3.95	2.47	2.45	2.45
(e) Travel time to the nearest Big Four by the road network [hour]						
Mean	0.88	0.66	0.56	0.50	0.49	0.48
Std. Deviation	0.56	0.33	0.32	0.21	0.21	0.21
(f) Sum of travel times to the Big Four by the road network [hour]						
Mean	5.76	4.30	3.79	3.56	3.50	3.47
Std. Deviation	2.32	1.48	1.34	0.97	0.99	0.96
(g) Urban land in a cell's 1.5 km circle neighbourhood [sq. km]						
Mean	0.61	0.84	0.99	1.02	1.22	1.28
Std. Deviation	0.83	1.00	1.12	1.19	1.34	1.41
(h) Largest urban agglomeration in a cell's 1.5 km circle neighbourhood [sq. km]						
Mean	4.02	8.32	14.24	16.75	27.33	31.92
Std. Deviation	16.12	25.67	39.14	43.24	59.26	64.77

amount of urban land and the size of the largest urban agglomeration within 1.5 km of a cell rise progressively.

Models

The GEE model explains the proportion of urbanised area in a cell, based on proximity, accessibility and policy indicators. To avoid multicollinearity, we tested which proximity and accessibility indicators best explained the outcome by calculating the Wald statistics of various models. Comparing the performance of models with various predictors led to several interesting observations. First, there is marginal difference between models with rail accessibility indicators and those with road accessibility indicators. Second, models with travel time variables have a better fit than those using Euclidian distances to transport nodes. Third, models with the amount of urban land within 1.5 km have a much higher goodness of fit than those with the size of the largest urban agglomeration within 1.5 km.

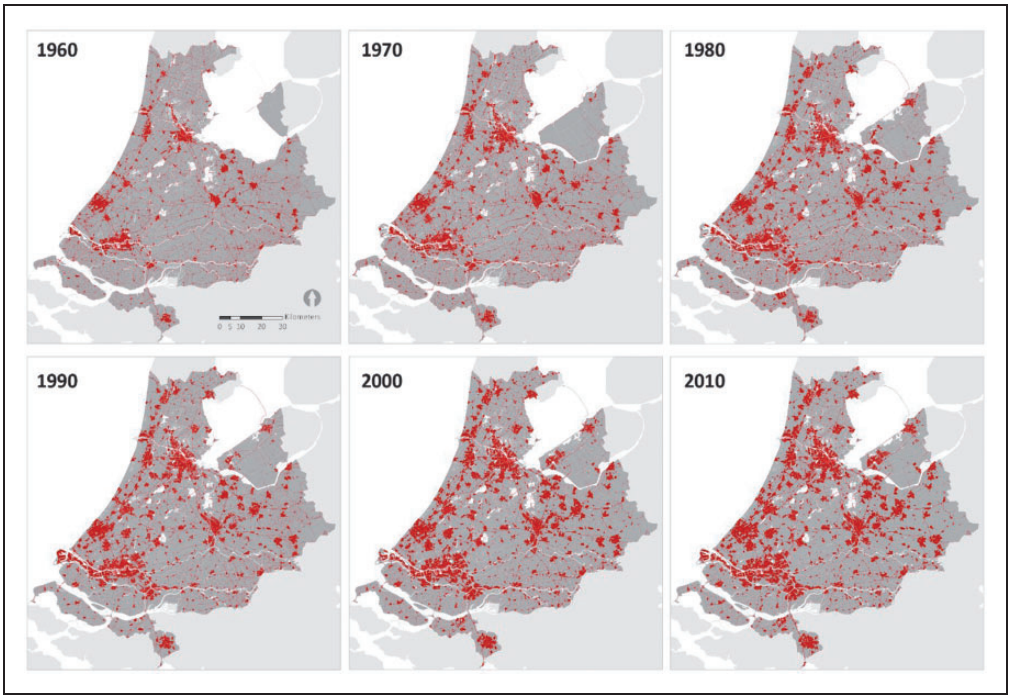

Figure 2. Urbanisation of the Greater Randstad Area (1960–2010).

The chosen model (with the highest Wald statistics) and its determinants are presented in Table 2 (for the detailed model selection procedure see Kasraian, 2017).

Table 2 reports the main coefficient of each determinant, that is, its effect at base year 1960. Interactions for each determinant with each time point are basically the effects of that variable at that time point *compared to* the base year (1960), or more precisely, the difference of the coefficient at that time point with the base year. They show whether and to what extent each determinant's impact varies over time.

For interpretation, "decade-specific" coefficients were calculated which are the sums of coefficients for the main and interaction effects for each time point. Time is treated as a categorical variable indicated by decades. Since 6 decades are involved, 5 time interactions with each predictor are modelled for decades 1970, 1980, 1990, 2000 and 2010, each compared with 1960. Standard errors and p-values are not reported since the model was estimated on the full population. The sequence of observations is expected to have no effect on the outcome, as the working correlation structure is exchangeable, assuming similar correlations between observations.

The exponentiation of coefficients yields odds ratios, indicating changes in the odds of urbanisation in a cell. For instance, the 0.955 odds ratio of *sum of travel times to the Big Four by rail* implies that with every hour increase in the total travel time to the Big Four, the ratio of urbanised proportion of a cell over its non-urbanised proportion will be reduced by 0.955. This equals a 4.5% reduction in the odds of urbanisation. Note that this effect is for the base year 1960. To see the variation in the effect of *sum of travel times to the Big Four* on urbanisation per time point, we calculate the decade-specific coefficient by adding the coefficient of interaction effect to the main one (Allison, 2009). For instance, the decade-specific coefficient for 1970 is $-0.046 + 0.011 = -0.035$. The amount of urban land in a cell's neighbourhood is shown to

Table 2. GEE model of the proportion of urban land in a cell.

	Coefficient	Odds ratio	Decade-specific coefficient	Decade-specific odds ratio
Main coefficients				
Sum of travel times to the Big Four by road	−0.046	0.955		
Urban land in a cell's neighbourhood	1.079	2.943		
Growth Centre	0.053	1.054		
Vinex	0.025	1.026		
Green Heart	−0.288	0.750		
Interactions with time				
*Sum of travel times to the Big Four by road*decade*				
1970	0.011	1.011	−0.035	0.965
1980	0.015	1.015	−0.031	0.970
1990	0.002	1.002	−0.044	0.957
2000	0.010	1.011	−0.035	0.965
2010	0.011	1.011	−0.035	0.965
*Urban land in a cell's neighbourhood*decade*				
1970	−0.060	0.942	1.020	2.772
1980	−0.085	0.919	0.995	2.704
1990	−0.075	0.928	1.004	2.730
2000	−0.117	0.889	0.962	2.617
2010	−0.124	0.883	0.955	2.598
*Growth Centre*decade*				
1970	0.048	1.049	0.101	1.106
1980	0.123	1.130	0.175	1.192
1990	0.127	1.135	0.180	1.197
2000	0.118	1.126	0.171	1.187
2010	0.112	1.118	0.165	1.179
*Vinex*decade*				
1970	−0.183	0.832	−0.158	0.854
1980	−0.296	0.744	−0.270	0.763
1990	−0.435	0.647	−0.410	0.664
2000	−0.074	0.929	−0.048	0.953
2010	0.471	1.602	0.497	1.643
*Green Heart*decade*				
1970	0.090	1.094	−0.198	0.820
1980	0.133	1.142	−0.156	0.856
1990	0.077	1.080	−0.211	0.810
2000	0.077	1.080	−0.211	0.810
2010	0.100	1.105	−0.189	0.828
Decade				
1970	−0.002	0.998		
1980	−0.024	0.976		
1990	−0.041	0.960		
2000	−0.026	0.974		
2010	−0.058	0.944		
Constant	−2.900	0.055		
Wald chi2 (35)	31,196.10			

Number of observations: 227,346; number of groups: 37,891.

have a very high impact on its odds of urbanisation. Every extra square kilometre built-up area in a cell's circle neighbourhood with a radius of 1.5 km almost triples its odds of urbanisation. While this impact witnesses a slight reduction, it can be considered relatively stable over time.

Elasticities facilitate comparisons of the impact of unstandardised variables, but cannot be calculated for models including dummy variables. Elasticities based on a model which only includes the chosen transport accessibility and urban proximity indicators confirm that the impact of urban proximity is much larger (not presented due to lack of space). The results indicate that a 1% increase of total travel times to Big Four decreases urbanisation by 0.006, while a 1% increase of urbanised area in the 1.5 km circle neighbourhood of a cell increases urbanisation by 0.144.

Being located in a Growth Centre or a Vinex location at year 1960, slightly increases the odds of urbanisation. However, the trend in odds ratios over time is more informative: the odds of urbanisation for a cell in a Growth Centre witness an increase of 10.6% (1970), 19.2% (1980), 19.7% (1990), 18.7% (2000) and 17.9% (2010). The remarkable rise in the urbanisation odds from 1970 to 1980 indicates the effect of the Growth Centres policy during the 1970s, i.e. a decade after its introduction. Being in a Vinex location actually reduces the chance of a cell's urbanisation up to and including 2000. However, the odds of urbanisation in a Vinex location rise substantially to 64.3% at 2010. The significant difference between the decade-specific odds ratios in 2000 and 2010 demonstrates the drastic role of the Vinex policy introduced in the 1990s on the spatial distribution of urbanisation in the 2000s. The Green Heart policy shows a strong restrictive effect at 1960 which remains stable over time.

The trend in the interaction of Growth Centres policy with time reveals an important issue: the effect of policies are likely to be durable and the legacy of a former policy could be long at work even when it is replaced by new policies over time. Thus, the Growth Centres policy of the 1960s has not only had an observable impact in the growth patterns of that decade, but has attracted new urbanisation ever since, regardless of the shifts in predominant spatial policies in the Randstad.

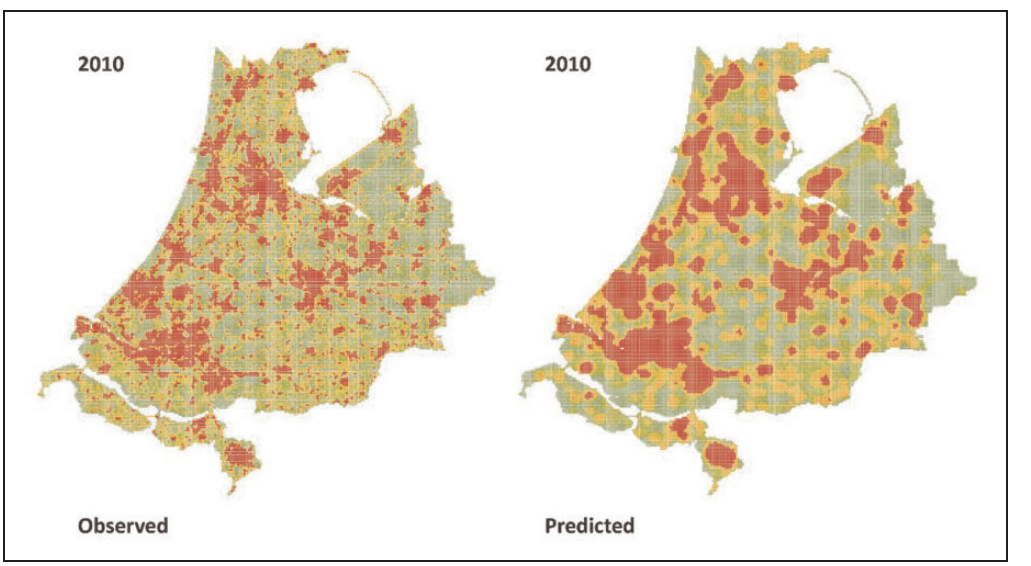

Figure 3. Observed versus predicted built-up areas for 2010 (quartile values from low to high: light green, green, orange and red).

Note that the coefficients for the main effects of the decades at the bottom of Table 2 show the effect of that decade on the urbanisation of a cell which does not belong to a Growth Centre, Vinex location or the Green Heart, has zero travel time to the activity centres and zero urban land in its neighbourhood, compared to the base year 1960. Figure 3 compares the actual versus predicted values for the built-up areas for year 2010 and shows that the GEE model performs well. While the model predicts the potential area likely to be developed based on proximity, accessibility and policy, in reality a smaller subset of this area is needed and actually built.

Conclusion and discussion

This paper aimed to find the extent to which transport accessibility, proximity to existing urban areas and spatial policies affect the dynamics of urbanisation, based on three assumptions which were tested by applying GEE-analysis to a panel of cells in the Randstad area (1960–2010).

The first assumption – that the process of urbanisation is driven by transport accessibility, with road accessibility being more influential than rail accessibility – is partially confirmed. Transport accessibility has had a stable but marginal influence on the spatial distribution of urbanisation. The impacts of rail and road accessibility on urbanisation dynamics are almost equal. Travel time accessibility indicators based on the network provide a better explanation for the likelihood of urbanisation than Euclidian proximity distances. The chosen accessibility variable – the sum of travel times to the Big Four – includes the time cost of travelling to major destinations (the Big Four) whose attractions are assumed approximately equal. We assume that the position towards major destinations, together with the proximity to nearby destinations influence urbanisation. Theoretically, however, potential accessibility measures combining a positive function of destination size with an inverse function of travel cost to all destinations, are likely to capture travel behaviour. Nevertheless, their calculation requires reliable historical travel behaviour data which are unavailable over the half-a-century study period.

It is surprising that the influence of the rather stable railway network is comparable to the influence of the road network which has witnessed drastic developments over the same period. This finding contradicts previous studies which for the most part have reported significantly higher impact for road compared to rail on land use change (Kasraian et al., 2016). This could be due to the dense Randstad railway network existing as of 1960 and the fact that the motorway network is constructed relatively parallel to the existing railways to bundle infrastructures. Moreover, Dutch anti-sprawl policies have recurrently encouraged developments at areas with high rail accessibility. Another reason could be the disutility of living in car-dependent areas in a dense metropolitan region like the Randstad with its congestions and parking limitations. Finally, the comparable impact of the rail and road networks on urbanisation patterns is derived from the network accessibility indicator to the Big Four. While large cities are highly accessible by both road and rail, accessibility to and the odds of urbanisation in smaller urban areas could be more dependent on road than rail.

Another important finding is that while the effect of transport accessibility is positive, it is rather marginal. This could be related to a number of issues. First, the effect of transport accessibility could have also been captured by urban proximity as these two are correlated to a certain extent: areas with high network accessibility are usually highly urbanised areas where people live. Second, changes in transport accessibility were not substantial during the study period. While this period witnessed the introduction and the development of the

motorway network, this network still developed more or less parallel to Randstad's already existing dense railway network. Thus, the longitudinal effect of developments in transport networks on urbanisation patterns within the Randstad has not been as drastic as for instance when the first railways were introduced into pedestrian cities. Third, the focus is on the distribution of urban growth *within* the Randstad. Compared to its peripheral regions, the Randstad experienced a much more rapid urbanisation, very likely at least partly due to its dense transport network and high transport accessibility. Fourth, the poly-nuclear structure of the Randstad area consisting of many medium sized and larger cities and towns could have played a role. Here, unlike monocentric metropolitan regions such as London and Paris, sharp differences between urban and rural areas and high variations in the distribution of transport infrastructure and urban land do not exist. Overall, these arguments show that stimulating and guiding urbanisation only by investing in transport infrastructures is ineffective in areas with saturated networks and accessibility. In other words, in an era and location where transport networks and their provided accessibility are saturated, significant change in land use can only be triggered by custom (integrated) transport and land use policies (see also Kasraian et al., 2016).

The second assumption was that existing urban areas drive urbanisation, with larger urban areas encouraging more urbanisation compared to smaller ones. This assumption is corroborated by the finding that the impact of existing urbanised areas in a cell's vicinity has a major influence on attracting urbanisation. Between urban proximity indicators, the amount of urban land within a cell's 1.5 km has a much higher explanatory power than the size of the largest urban agglomeration in the same neighbourhood. Importantly, the impact of urban proximity is shown to be a more powerful driver of urbanisation patterns than transport accessibility and spatial policies.

The third assumption was that spatial policies guide urbanisation. This assumption is confirmed as spatial policies are shown to have played a significant role in channelling the new urbanisation and preserving green areas, contrary to many countries where autonomous market forces are dominant. Among all policies, the Green Heart policy has continuously exerted a restrictive effect on urbanisation in this preserved area. The Growth Centres have had a significant impact, especially in the 1970s, by attracting urbanisation and diverting it from more rural locations. The Vinex policy is shown to have drastically influenced the growth patterns of the 2000s. The effects of both Growth Centres and Vinex policies become observable in the urbanisation patterns of the first decade after their introduction.

Our findings on the significant role of spatial policies are in line with previous works which have claimed the success of the Concentrated Deconcentration and Growth Centres policies in the 1960s and the 1970s, as well as the Compact City and Vinex policies of 1980s and 1990s in redirecting urban sprawl (Dieleman and Wegener, 2004; Dieleman et al., 1999; Faludi and van der Valk, 1994; Geurs and van Wee, 2006). The added value of this work is that it empirically shows the success of these policies in redirecting urbanisation and demonstrates the time period during which the policies have become effective. At this point, it is too early to judge the effect of the decentralisation promoted by the Network Cities policy.

A remarkable conclusion is the durability of previous policies. A policy's legacy can affect development patterns decades later when newer concepts are introduced. Implementation of the Concentrated Deconcentration policy through Growth Centres in the 1960s not only had an observable impact in the growth patterns of the 1970s, but has attracted new urbanisation since. Thus, the Growth Centres policy has remained influential regardless of the shifts in predominant Dutch spatial policies to the Compact City and Vinex in the following decades. Due to the durability of policies, a former policy could affect developments for decades and

even its discontinuation will not guarantee the restoration of the situation to the pre-policy era.

Finally, it is useful to reflect on how policies are applied and the complementary role of autonomous or market forces. In the Netherlands, planners and policy makers provide guidelines for development usually at the national level, which are then translated into designated locations at the local scale. For instance, Vinex location guidelines included building near existing cities and public transport. These guidelines were then translated to earmarked locations by the municipalities. In our model, guidelines' impacts are captured by variables showing a cell's distance to transport infrastructure and the amount of urban land in its vicinity. Furthermore, the effect of the guidelines' direct interpretation is included as dummy variables for the defined Vinex/Growth Centre/Green Heart boundaries. However, it is difficult to disentangle the effect of policy from market forces, as the latter can reinforce or nullify the first. Variables measuring transport accessibility and urban proximity also capture the impact of market forces. From a market perspective it is also favourable to build close to transport infrastructure nodes and urban agglomerations, which entails easier access to labour, resources and the advantage of the economies of scale. Regarding the Growth Centres policy it can be argued that autonomous processes followed and reinforced the trend initiated by policy. The Growth Centres policy encouraged urbanisation in specific areas which later became existing urban areas and attracted further urbanisation. Overall, the final situation is indeed the resultant of both the efforts of policy and market forces.

The paper is a step towards the accurate analysis of urbanisation which is urgently needed to formulate efficient territorial policies, especially in the European context (Salvati and Carlucci, 2015). Moreover, the findings could be relevant for other comparable poly-nuclear areas in developed countries with saturated development and transport accessibility, such as the Ruhr region in Germany, the urbanised part of Flanders in Belgium and the San Francisco Bay Area in the US. What this paper highlights, and what could possibly be applied in other regions, is that spatial policies help to curb urban sprawl. This is relevant, as the Belgian Flanders experiments with the compact city, some German cities with densification, and North American cities with the congeneric Smart Growth policies. However, future research is needed to bring to light whether those regions follow the same patterns concerning urban proximity versus accessibility, road versus rail, and the role of spatial policies.

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