The Influence of Built Environment Characteristics on the Occurrence of Crime in Neighbourhoods of Amsterdam: A Geographically Weighted Regression Analysis

Gamze Dane, Stephan Leeuw, Dena Kasraian, Aloys Borgers

(Dr. Gamze Dane, Department of the Built Environment, Eindhoven University of Technology, 5612 AZ, Eindhoven, The Netherlands, g.z.dane@tue.nl)

(MSc. Stephan Leeuw, Department of the Built Environment, Eindhoven University of Technology, 5612 AZ, Eindhoven, The Netherlands, stephanaleeuw@gmail.com)

(Dr. Dena Kasraian, Department of the Built Environment, Eindhoven University of Technology, 5612 AZ, Eindhoven, The Netherlands, d.kasraian@tue.nl)

(MSc. Aloys Borgers, Department of the Built Environment, Eindhoven University of Technology, 5612 AZ, Eindhoven, The Netherlands, a.w.j.Borgers@tue.nl)

1 ABSTRACT

Crime in neighbourhoods has a significant impact on the quality of life and safety of the residents. There are theories that suggest the relation between the built environment characteristics and the occurrence of crime. These theories suggest that designing the built environment in a particular way could reduce the number of criminal activities, the fear of crime and the victimisation of residents and legitimate users of the area. However, there is little empirical research on this topic.

In recent years, the amount of open and spatial data has increased which enables to test these theories empirically. This current study aims to understand the influence better of built environment characteristics on the amount of crime in the neighbourhoods in Amsterdam by using open and spatial data. In this study, firstly existing theories on the relation between crime and built environment characteristics (i.e. land use, street layout, the existence of parking amenities, the existence of greenspace, the existence of street lighting) were discussed. Later, the influence of selected built environment characteristics on the amount of crime in Amsterdam neighbourhoods was empirically tested. Data regarding crimes was obtained from the Dutch police department. It provides crime rates per crime type (burglary, vandalism, violent crimes, drugs and nuisance, and theft) and per neighbourhood. The data regarding built environment characteristics were gathered from Open Street Map and Amsterdam open data, and they were processed for further analysis.

In order to look into the relation between the occurrence of crime in neighbourhoods of Amsterdam and the built environment characteristics, firstly an exploratory regression analysis was performed on the different crime types, and then a geographically weighted regression analysis was conducted to identify local variations. The results show that different types of crime were influenced by different characteristics of the built environment. Moreover, variations in the neighbourhoods were observed. One of the findings of this research is that tourist attractions strongly correlate with the amount of crime. Another interesting finding is that mixed land-use is negatively correlated with the amount of crime. In general, it can be concluded that the built environment does have an influence on the occurrence of crime and that this influence differs among crime types. Moreover, different characteristics of the built environment influence different types of crime. The results of this study provide insights for policy recommendations both for necessary data and urban design with respect to crime prevention.

Keywords: geographically weighted regression, environmental criminology, crime prevention through environmental design (CPTED), geographical information systems (GIS), urban planning

2 INTRODUCTION

The relation between crime and the built environment has been researched relatively little. However, research that has been done reports that designing the built environment in a particular way could reduce the number of criminal activities, the fear of crime and victimisation of residents and legitimate users of the area. In 1961, Jacobs postulated in The Death and Life of Great American cities [1], that the urban environment could affect the behaviour of users in the area, especially that land-use diversity and a high pedestrian activity influence the perception of safety positively. Subsequently, Newman (1972) developed the defensible space theory in the early 1970s [2]. The defensible space theory is characterised by low urban density with high proportions of residential areas with limited access to strangers. Also, in 1971, Jeffery introduced the term Crime Prevention Through Environmental Design (CPTED) [3]. All these contributions were aimed to reduce crime by shaping the built environment.

This current study aims to understand empirically which characteristics of the built environment, socio-demographics and socio-economics have influence on crime numbers of different types of crimes in the neighbourhoods of Amsterdam. In this research, the following types of crime are considered: burglary, vandalism, violent crimes, drugs and nuisance related crimes and theft. Moreover, all crimes combined were analysed. The unit of analysis was selected as the neighbourhoods of Amsterdam.

This paper is organised as follows: First literature on the relation between the built environment and crime is presented. Then, methodology and data is introduced. Following that, analyses are conducted and noticeable results per crime type are discussed. The paper concludes with a discussion of findings and suggestions for policy makers.

3 LITERATURE REVIEW

Jane Jacobs was one of the first who established a relation between the physical environment and crime. Jacobs (1961) argued that crime occurs when residents feel isolated and anonymous, and when they believe that they have no stake in their neighbourhood [1]. Jacobs proposed four conditions of urban design: (I) mixed land-uses to stimulate pedestrian activity on the streets and parks; (II) districts should be divided into small blocks with frequent corners and interconnecting streets; (III) diversity of old and new buildings to ensure diversity of enterprises; (IV) a sufficient population density to stimulate activity among residents [4]. The four conditions all contribute to ‘’eyes on the street’’ which is the term Jacobs introduced for informal surveillance.

Oscar Newman (1972), an architect and urban designer, developed the defensible space theory in the early 1970s [2]. According to Donnelly (2010) [4], the defensible space theory has four key concepts: territoriality, surveillance, image and milieu. ‘’The four elements of defensible space can translate the latent territoriality and sense of community of residents into a responsibility to secure and maintain a safe, productive and well-maintained neighbourhood’’ (Cozens, 2008) [5]. Newman (1972) also argued that high-rise buildings and high urban density results in anonymity which in turn has an influence on the occurrence of crime [2].

The contributions of Jacobs (1961) and Newman (1972) formed the basis of what is now known as crime prevention through environmental design (CPTED) [1-2]. CPTED is considered to be mostly a ‘natural’ strategy in preventing crime which implies that it is not labour intensive. Fennelly & Crowe (2013) state that there are four principles of CPTED: (I) territoriality, (II) surveillance, (III) access control and (IV) image and maintenance. Territoriality is aimed at the demarcation of public and private space [6]. Natural surveillance is involved in creating more ‘’eyes on the street’’. The third principle, access control, relates to controlling the people in areas where they should not be. Finally, the principle of maintenance and image, concerned with appearance of the area can be related to the broken window theory by Kelling & Wilson (1982) [7]. The theory describes how one broken window (which is not repaired immediately) could lead to a signal that no one cares about the neighbourhood, and thus that breaking more windows will cost nothing. The theory is not only concerned with the physical deterioration of the neighbourhood, but also the social ties. While not repairing a broken window sends a message about the area, it also sends a message about the residents, as they did not repair the window.

Below the relevant characteristics of the built environment that have been researched in relation to crime prevention, are discussed.

3.1 Land use

Jacobs (1961) mentioned the importance of different land uses in an area to improve pedestrian activity and thus increase the natural surveillance (eyes on the street) in the neighborhood [1]. The study by Wuschke & Kinney (2018) concluded that rates of property crimes and violent crimes are most present on residential land uses [8]. However, these types of crime occur disproportionally at a higher rate in areas classified as commercial or recreational.

3.2 Greenspace

According to de Vries, Verheij, Groenewegen, & Spreeuwenberg (2003), greenspace leads to more physical activity such as walking and cycling and therefore the presence of greenspace may have a positive effect on natural surveillance [9]. However, this positive effect on natural surveillance might also be dependent on the time of the day (Weijs-Perrée et al., 2020) [10]. Shepley, Sachs, Sadatsafavi, Fournier, & Peditto (2019) found in their extensive literature review of 45 quantitative researches that greenspace helps reducing crime [11]. Bogar & Beyer (2016) claimed that the current research body is too small and that there is too much variation among the researches to draw conclusions [12].

3.3 Street lighting

Street lighting is commonly mentioned in studies regarding CPTED, as it increases visibility and therefore also increases the natural surveillance (Gulak, Kun, Koday, & Koday, 2007; Hedayati Marzbali, Abdullah, Ignatius, & Maghsoodi Tilaki, 2016; Hedayati Marzbali, Abdullah, Razak, & Maghsoodi Tilaki, 2012; Lee, Park, & Jung, 2016) [13-16]. Moreover, Lee et al., (2016) found that streetlighting reduces the fear of crime and that it increases pedestrian activity [16].

3.4 Street layout

The design of infrastructure is associated with the access control principle of CPTED. Sohn (2016) found the street density and intersection density to be significantly correlated with residential crime density [17]. Block & Block (1995) found that many, liquor related crimes occur near intersections, especially in grid and diagonal street patterns [18].

Newman (1972) argued that cul de sacs (dead end streets) are the streets where crime occurs the least, as small group of neighbours can survey the area that is accessible from their dwelling (Hillier, 2004) [2,19]. Moreover, Yang (2006) showed that residential burglary occurs most on streets with ‘’through traffic’’ and the least on dead-end streets [20]. This is contrary to the argument of Jacobs’ (1961), which stated that areas should be well connected in order to create a more vibrant area where informal surveillance acts as a mechanism against crime [1].

3.5 Parking

Limited (public) parking places is believed to have a positive effect on access control, and furthermore, the fewer cars that are parked, the fewer the opportunities for car related crimes. Moreover, Bennet & Wright (1984), found that burglars look for parked vehicles in the immediate area next to their target as a sign of occupancy [21]. By limiting the number of parking places, it is more likely that they are occupied, and therefore, a higher percentage of the parking places is occupied.

3.6 Housing

“Scholars have long known that home-owners and long-term residents have a greater incentive to protect their local area and might be willing to take more risk in so doing’’ (Felson, 2018) [22]. Hence it could be argued that the number of rented (or owned) homes is of importance in this research.

Vacancy is often mentioned as a determinant of the image and maintenance principle of CPTED. The study conducted by Fuentes & Hernandez (2014) regarding property crime and vacancy, found that for every point increase in vacancy, the number of property crime rose by .84% [23]. Moreover, Cui & Walsh (2015) found that violent crime increased by 19% in the immediate area once a foreclosed home became vacant [24].

Another determinant of crime, in relation to housing, is population density. A high population density is facilitated by high-density housing. Sampson & Groves (1989) found in their study in which they tested the social disorganisation theory that the level of urbanisation is significantly positive correlated with multiple types of crime [25]. They argued that a high level of urbanisation weakens local social structures (decreased social control, weakened local kinship and friend networks). These findings are supported by the finding of Sohn (2016) [17].

3.7 Artworks

According to Fennelly & Crowe (2013) “Art and sculpture are powerful tools in promoting territorial behavior and proprietary concern for space. They attract attention to spaces and help people find their way. One of the greatest values of street art is how it contributes to triangulation, which helps people psychologically connect places, thus increasing perceptions of territoriality and control.’’[6]. However, no empirically research was found in which artworks and cultural heritage symbols are tested against crime.

3.8 CCTV

The presence of closed circuit television (CCTV) is a mechanical crime prevention method which is aimed at increasing surveillance. Lee, Park, & Jung (2016) argued that the presence of CCTV also provides symbolic barriers that deter criminals and thus CCTV could besides surveillance, also be effective as a mean of access control [16]. Hedayati Marzbali, Abdullah, Ignatius, & Maghsoodi Tilaki (2016) used a similar reasoning [14].

3.9 Tourist attractions

It is generally known that the city of Amsterdam is a tourist intensive city; in 2018 the city was ranked 23rd in the top 100 city destinations by Euromonitor (Geerts, 2018) [26]. Bhati & Pearce (2016) stated that many tourist sites experience vandalism [27]. Moreover, Merrill (2011) stated that cultural heritage monuments/areas are often vandalised with graffiti, which is a textbook example of vandalism [28]. Crime types that occur most due to tourist attractions are vandalism and theft related crimes (Bhati & Pearce, 2016; Jud, 1975) [27,29]. Jud (1975) found that tourism is mainly concerned with property related crimes [29].

3.10 Social disorganisation

Whereas this research is mostly concerned with the physical part of environmental criminology, it is also necessary to include socio-economic and socio-demographic variables as control variables, since crime prevention is a multi-disciplinary and integrated endeavor (United Nations Office on Drugs and Crime, n.d.) [30]. The social disorganisation theory will be used for determining the socio-economic and demographic variables. The social disorganisation theory is considered to be one of the most influential contributions to environmental criminology on the meso-level of analysis, besides the contribution of Jane Jacobs (Wortley & Mazerolle, 2008) [31].

The social disorganisation theory, in short, states that three variables cause social disorganisation. These variables are (I) the physical state of the neighbourhood, (II) the economic status and (III) ethnic heterogeneity. Shaw & McKay (1942) argued that all these three variables contribute to creating social disorganisation, which in turn results in higher crime and delinquency rates in the neighbourhood [32].

The physical state was defined by the population change, vacant and condemned housing and the proximity to industry. Shaw & McKay (1942) argued that high residential mobility makes it difficult to create a social structure in the neighbourhood [32]. Rogerson & Pease (2019) also mentioned that high residential mobility is a challenge for CPTED [33]. Rogerson & Pease (2019) also found that crime in neighbourhood results in motivation to move [33].

Shaw & McKay (1942) argued that ethnic heterogeneity in the population also affects the social structure in the neighbourhood [32]. Ethnic heterogeneity is often solely used as a measure of social disorganisation. Often the heterogeneity index, developed by Blau (1977) is used [34], which is a measure indicating the level of ethnic heterogeneity on a scale from zero to one (Bruinsma, Pauwels, Weerman, & Bernasco, 2013; Davies & Bowers, 2018; Kimpton, Corcoran, & Wickes, 2017; Sampson & Groves, 1989) [25, 35-37].

The literature review revealed that the relation between the built environment and crime has been theorised extensively. Moreover, specific characteristics of the built environment were found to be correlated with crime. In general, these characteristics can be classified into one or more principles of CPTED.

4 MATERIALS AND METHODS

In this section, first the collection of the data and the operationalisation of this data is discussed. Subsequently, the exploratory regression, the ordinary least squares regression and finally the geographically weighted regression analysis are elaborated.

4.1 Data

Data regarding crimes were obtained from the Dutch police department [38]. It provides crime rates per crime type (burglary, vandalism, violent crimes, drugs and nuisance, and theft) and per neighbourhood. In this study, per neighbourhood, the crime density was determined by dividing the number of crimes by the area of the neighbourhood. A square root transformation was performed on the crime density to create a more normal-like distribution. Logarithmic transformations were not considered due to crime densities of less than one or even zero. The operationalisation of the independent variables is displayed in Table 1.

Variable	Operationalisation	Mean	Min	Max	Std. Dev.	Data source
Cul-de-sac density	# of dead-end streets per square kilometer	21.659	0.000	167.040	23.349	Rijkswaterstaat [39]
Intersection density	# of intersections per square kilometer	146.574	1.363	605.945	79.895	Rijkswaterstaat [39]
Mixed land-use	Heterogeneity index[1]	0.554	0.000	0.915	0.206	PDOK [40]
Percentage of residential land-use	Ratio of land covered by residential land-use	0.521	0.000	1.000	0.295	PDOK[40]
Percentage of retail and catering land-use	Ratio of land covered by retail and catering land-use	0.075	0.000	0.890	1.567	PDOK[40]
Ratio CCTV coverage	Ratio of land covered by CCTV coverage	0.095	0.000	1.000	0.246	Municipality of Amsterdam [41]
Streetlighting density	# of streetlights per square kilometer	2418.775	19.508	6002.020	988.354	Open Data Dutch Government [42]
Artworks	# of public artworks per square kilometer	5.604	0.000	87.823	10.077	Municipality of Amsterdam [41]
Ratio Greenspace	Ratio of land covered by greenspace[2]	0.092	0.000	0.786	0.148	PDOK[40]
Tree density	# of trees per square kilometer	1205.577	0.000	3216.420	613.906	Municipality of Amsterdam [41]
Parking density	# of parking spots per square kilometer	2847.093	0.000	6954.150	1666.157	Municipality of Amsterdam [41]
Population density	# of inhabitants per square kilometer	13045.184	32.000	35855.000	8127.880	Statistics Netherlands [43]
Address density	# of addresses that are present within one kilometer	5746.099	28.000	12417.000	3240.471	Statistics Netherlands [43]
Vacancy rate	percent of vacant dwellings in the neighborhood	7.955	1.000	54.000	7.119	Statistics Netherlands [43]
Tourist attraction density	# of tourist attractions per square kilometer	6.257	0.000	129.599	15.821	Open Data Dutch Government [44]
Ethnic heterogeneity	Blau index [34]	0.642	0.184	0.819	0.115	Statistics Netherlands [43]
Socio-economic status	Sum of z-scores of (I) average real-estate value, (II) share of high educated residents and (III) labor participation.	0.000	-6.535	6.182	2.357	Statistics Netherlands [43,45]
Percentage of rented homes	Percentage of rented homes in the neighborhood.	67.124	3.000	100.000	20.821	Statistics Netherlands [43]

Table 1: Independent variables, their operationalization and descriptive statistics. [1]) Formula heterogeneity index: mixed land-use = (1-∑ki=1 Li2) / ((k-1)/k), Li: ratio land-use type i, k: number of different land-uses. [2]) A 50-meter buffer was created around greenspace outside of the research area, as it is believed that major greenspace areas influence the surrounding neighbourhoods.

4.2 Method

This study aims to understand the influence better of built environment characteristics on the amount of crime in the neighbourhoods in Amsterdam by using open and spatial data. Kubrin & Weitzer (2003) mentioned that researchers that research “social disorganisation” slowly start addressing the problem with aggregation of social data into officially defined areas in space [46]. They argued that this is problematic as these officially defined areas are seldom spatially independent and that crime levels in one neighbourhood influence crime levels in adjacent neighbourhoods. Cahill & Mulligan (2007) argue that one of the problems with global regression models is that possible variations over space are suppressed [47]. Hence, the use of a Geographically Weighted Regression (GWR) analysis is suitable for the aim of this study.

In order to conduct a GWR, the first step of the analysis is an exploratory regression which is aimed to find the most optimal combination of variables while minimising the corrected Akaike’s Information Criterion (AIC) for the Ordinary Least Square (OLS) regression model. It was expected that per crime type different variables would be included in the models. The model with the lowest score for AIC, see Akaike (1974), was selected for further analysis [48].

Next, an OLS regression analysis was performed with the variables which were obtained from the exploratory regression. This OLS regression provided coefficients and significance levels of the relevant variables. The residuals of the OLS regression were tested for spatial autocorrelation by using Moran’s I. This was done for verification purposes, as clustered residuals might interfere with the effectiveness of the geographically weighted regression. Moreover, it could also indicate that variables are missing which are apparent in areas with overpredictions and underpredictions.

The last step was to conduct a GWR analysis to identify spatial variability in the coefficients. The bandwidth for the fixed kernel was set at three kilometers. The literature suggests a bandwidth of approximately 2400 meter [Malczewski & Poetz (2005) & Cahill & Mulligan (2007) [47,49]. Concerning the research area, the minimum bandwidth is approximately 2200, suggesting each neighbourhood has at least one neighbour. Hence, a larger bandwidth was used to ensure that all neighbourhoods have sufficient neighbours. Using a larger bandwidth results in less variability in the results as the model will approach the OLS models.

5 RESULTS

In this section, the results of the analysis are discussed. First, the results from the ordinary least squares regression analysis are discussed. Afterwards, the section continues with the results from GWR per crime type.

5.1 Ordinary Least Squares Regression Results

The results of the exploratory regression analyses and ordinary least squares regression analyses are summarised in Table 2. The variables that came forward at the exploratory regression were included in the OLS regression. Variables without coefficient are variables that did not come forward in the exploratory regression and thus do not improve the model.

Looking at the results of the OLS regression analyses, it can be observed that all variables, except the cul-de-sac density, are included at least once in each model per crime type (burglary, vandalism, violent crimes, drugs and nuisance, theft and the combined model). Moreover, high significance levels can be observed. This is no surprise due to the prior executed exploratory regression which ensures that only relevant variables are included in OLS regression. The results of the OLS regression show global relationships and more generalisable results. In general, the results are in line with the literature, with a few exceptions; such as the greenspace in the burglary model and streetlighting for all models in which it is included. Moreover, CCTV has opposite signs, as was expected, as the literature suggest that CCTV should be effective in decreasing crime.

The most noticeable result of the burglary model is the variable greenspace. In regard to vandalism, streetlighting and artworks having a positive sign is contrary to the findings from the literature. On the other hand, it could be argued that streetlighting and artworks are targets of vandalism, and thus attract vandalism. The other models do not seem to have any notieeable or contradictory findings besides the earlier mentioned CCTV and streetlighting.

Variables	Burglary	Vandalism	Violent Crimes	Drugs and Nuisance	Theft	Combined Crimes
Constant	-.940	-.560	-.369	-.356	2.527**	2.869
Cul-de-sac density	-	-	-	-	-	-
Intersection density	.007***	-	-	.004	-	-
Mixed land-use	1.496**	-	-2.690***	-	-3.250***	-7.424***
Percentage of residential land-use	2.182***	1.131*	-	-	-	-
Percentage of retail and catering land-use	-	7.417***	18.418***	18.443***	26.662***	56.455***
Ratio CCTV	-1.111**	2.004***	2.792***	3.875***	3.230***	5.413***
Streetlighting	-	.00032*	.00042**	.00043*	.002***	.003***
Artworks	.022*	.027**	-	-	-	-
Ratio greenspace	1.911**	-	-	-	-	-
Tree density	-	-	-	-	-	-.001**
Parking density	-	-	.00027**	-.00043***	-	-
Population density	.000204***	.00007***	.00011***	.00005*	.00012***	-
Address density	.000134**	.00024***	.00038***	-	.00048***	.002***
Vacancy rate	.049**	-	.068**	.047*	.104***	-
Tourist attraction density	-	.019*	-	.099***	.146***	.212***
Ethnic heterogeneity	-	4.201***	7.585***	-	-	11.354***
Socio-economic status	-.099*	-	-.256***	-	.397***	.686***
Percentage rented homes	-	-	-	.016*	.032***	.064***
R2-adjusted	.530	.654	.709	0.724	.807	.877
AICc	1796.67	1865.54	2044.70	2120.61	2302.83	2650.37
Max VIF-value	2.670	2.829	3.088	2.088	3.002	2.285

Table 2:Results exploratory and ordinary least squares regression analyses. Note: *** variable significant at the $p<0.01$ level; ** variable significant at the $p<0.05$ level; * variable significant at the $p<0.10$ level; - not included

As a note, the residuals of all models were tested for spatial autocorrelation using Moran's I; the results are displayed in table 3. The residuals of all models were not found to be spatially autocorrelated as the p-value for all crime types was higher than 0.10. Hence, the residuals were distributed randomly throughout the research area.

Variables	Burglary	Vandalism	Violent Crimes	Drugs and Nuisance	Theft	Total Crimes
Constant	-.940	-.560	-.369	-.356	2.527**	2.869
Cul-de-sac density	-	-	-	-	-	-
Intersection density	.007***	-	-	.004	-	-
Mixed land-use	1.496**	-	-2.690***	-	-3.250***	-7.424***
Percentage of residential land-use	2.182***	1.131*	-	-	-	-
Percentage of retail and catering land-use	-	7.417***	18.418***	18.443***	26.662***	56.455***
Ratio CCTV	-1.111**	2.004***	2.792***	3.875***	3.230***	5.413***
Streetlighting	-	.00032*	.00042**	.00043*	.002***	.003***
Artworks	.022*	.027**	-	-	-	-
Ratio greenspace	1.911*	-	-	-	-	-
Tree density	-	-	-	-	-	-.001**
Parking density	-	-	.00027**	-.00043***	-	-
Population density	.000204***	.00007***	.00011***	.00005*	.00012***	-
Address density	.000134**	.00024***	.00038***	-	.00048***	.002***
Vacancy rate	.049**	-	.068**	.047*	.104***	-
Tourist attraction density	-	.019*	-	.099***	.146***	.212***
Ethnic heterogeneity	-	4.201***	7.585***	-	-	11.354***
Socio-economic status	-.099*	-	-.256***	-	.397***	.686***
Percentage rented homes	-	-	-	.016*	.032***	.064***
R2-adjusted	.530	.654	.709	0.724	.807	.877
AICc	1796.67	1865.54	2044.70	2120.61	2302.83	2650.37
Max VIF-value	2.670	2.829	3.088	2.088	3.002	2.285

	Burglary	Vandalism	Violent Crimes	Drugs and Nuisance	Theft	Combined Crimes
Moran's I 1	0.005360	0.002210	0.000396	0.001985	0.000238	-0.000081
Z-score	1.411898	0.855496	0.520057	0.811449	0.491463	0.433635
P-value	0.157980	0.392277	0.603024	0.417108	0.623099	0.664553

Table 3: Results test for spatial autocorrelation using Moran's I per crime type. Note:1 Bandwidth 3000-meter, Euclidean distance method.

5.2 Results of Geographical Weighted Regression per Crime Type

Per crime type a geographically weighted regression was performed. In this subsection, these analyses and their results are elaborated per crime type.

5.2.1 Burglary

The results of the GWR for the burglary model are displayed in Table 4. The differences in the coefficients and local R-squared values show that there are changing relationships per neighbourhoods. The improvement of the adjusted R-squared value and the AIC shows that taking spatial relationships into account is beneficiary.

	Lowest	Mean	Highest
Intercept	-3.273	-1.115	1.946
Intersection density	0.001	0.007	0.020
Art density	-0.026	0.025	0.105
Ratio CCTV	-5.054	-1.434	0.097
Percentage residential land-use	-3.504	2.327	4.999
Mixed land-use	-5.559	1.147	2.505
Socio-economic status	-0.471	-0.046	0.280
Ratio greenspace	-1.132	1.341	8.127
Population density	0.00005	0.00020	0.00046
Address density	-0.00023	0.00017	0.00037
Vacancy rate	-0.040	0.058	0.158
Local R-squared	0.480	0.548	0.883

Table 4: Results GWR burglary model. R2-adjusted: 0.563; AICc: 1766.98

Looking at the burglary model from the GWR, the most interesting findings are the intersection density and the socio-economic status. The intersection density perfectly follows the empirical results of Sohn (2016) & Yang (2006) [17, 20]. On the other hand, it is contrary to Jacobs' (1961) argument of increased permeability which should decrease crime [1]. Socio-economic status having positive and negative coefficients is also found to be interesting, as it suggests that burglaries should occur the least in areas with a socio-economic status that is close to the mean.

In Figure 1a, the local R-squared values are displayed. It can easily be observed that the model performs better in peripheral areas of the city, whereas the model performs worse in the city centre. The model performs better in areas with a lower number of burglaries. This implies that the variables explain less variance in the city centre and more in the peripheral areas. The city centre has a relatively large negative coefficient for the intercept (Figure 1b). This could possibly be due to one or more missing variables that could have been added to the regression analysis. This could also explain the lower R-squared values in the city centre, as less variance is found by the model in this specific region. Population density which has the highest standardised coefficient in the OLS regression, seems to have a somewhat random pattern considering the areas with a high number of burglaries in combination with highly populated areas (Figure 1c).

In Figure 1d, the coefficients of the socio-economic status are displayed. As the values for the socio-economic status range between approximately -6 to 6, this in combination with coefficients ranging from approximately -0,5 to 0,3 makes the GWR results relatively difficult to interpret. Neighbourhoods with a poor socio-economic status and also a negative coefficient would experience more burglaries, as multiplying negative values will become positive. On the other hand, neighbourhoods with a high socioeconomic status and also a positive coefficient will also experience more burglaries.

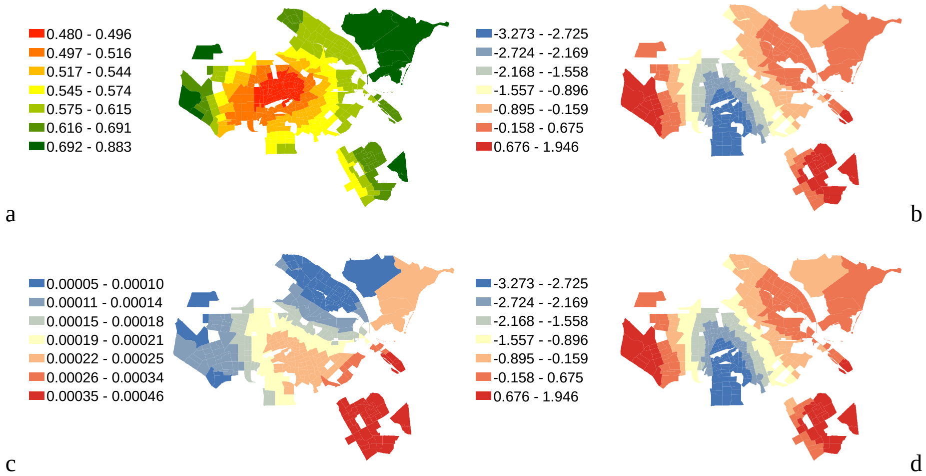


Figure 1: Maps representing results GWR burglary model (a) Local R-squared values; (b) Coefficient intercept burglary model; (c) Coefficient population density burglary model; (d) coefficient socio-economic status.

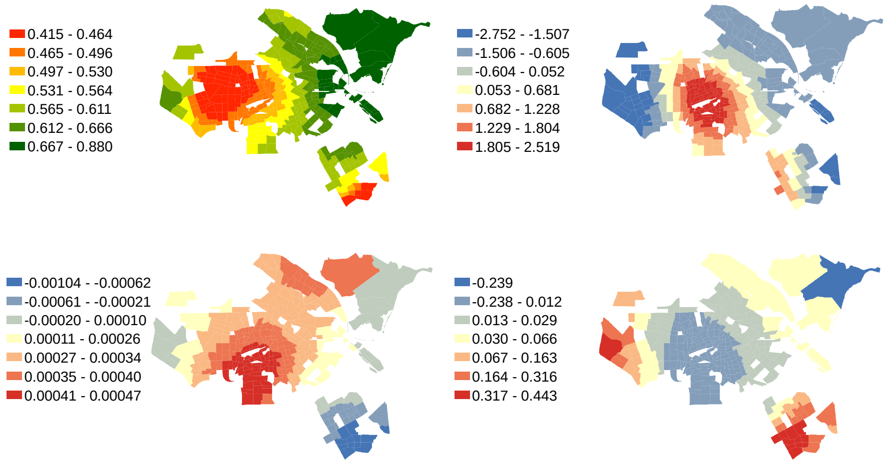
5.2.2 Vandalism

The results of the vandalism model are displayed in Table 5. It is observed that there are varying relationships. The adjusted R-squared and AICc indicate a significantly better model fit than the OLS regression model. The most interesting finding of the vandalism model is the high positive correlation with tourist attractions, which was initially unexpected. However, the literature suggested that this correlation does make sense (Bhati & Pearce, 2016; Merrill, 2011) [27,28].

	Lowest	Mean	Highest
Intercept	-2.752	0.415	2.519
Art density	-0.067	0.026	0.085
Ratio CCTV	-0.057	2.691	4.086
Ethnic heterogeneity	-0.895	2.705	12.364
Percentage residential land-use	-1.811	1.100	3.442
Percentage retail and catering land-use	-6.147	6.770	15.601
Tourist attraction density	-0.239	0.041	0.443
Streetlighting density	-0.00027	0.00019	0.00074
Population density	-0.000013	0.000083	0.000359
Address density	-0.00104	0.00025	0.00047
Vacancy rate	-0.040	0.058	0.158
Local R-squared	0.415	0.549	0.880

Table 5: Results GWR vandalism model. R2-adjusted: 0.666; AICc: 757.00

It can be observed that the model performs worst in the west area of the city centre, whereas it performs best at the east and north of the city centre. The local R-squared values for areas with many vandalism related crimes, seem to differ (Figure 2a). The intercept is the highest in the city centre, while the peripheral areas have lower coefficients (Figure 2b). Arguably, the intercept might compensate for variables which are not included but that could have stimulated vandalism, since the local R-squared values are also the lowest near the city centre where vandalism occurs the most. Looking at the coefficients for the address density (figure 2c), it stands out that the southeast region has a negative coefficient. This pattern could be explained as the literature shows that more urbanised areas experience more crime. Unexpectedly, tourist attractions density has the lowest coefficients in the area where most tourist attractions are located (figure 2d). A possible explanation is that the tourist attraction density is much higher in that area and that the model uses a lower coefficient to somehow compensate this by giving tourist intensive areas lower coefficients.



a b c d

Figure 2: Maps representing results GWR vandalism model (a) Local R-squared values; (b) Coefficient intercept vandalism model; (c) Coefficient address density vandalism model; (d) coefficient tourist attraction density vandalism model.

5.2.3 Violent Crimes

Table 6 shows the results for the violent crimes model. Like the vandalism model, a significant model fit improvement can be observed. The most interesting results of the violent crimes model are that a large number of variables included are perfectly in line with the literature; variables originating from the social disorganisation theory, vacancy, mixed land-use and retail and catering land-use. Looking at the local R-squared values, there are areas in Amsterdam in which 90 percent of the variance can be explained by the GWR model (Figure 3a). A clear division between east and west can be observed; in the east high values are present, whereas the lowest values appear in the west. The city centre where most violent crimes occur, has a R-squared value that is slightly higher than the mean.

	Lowest	Mean	Highest
Intercept	-3.692	0.412	5.238
Parking density	-0.000801	-0.000268	0.00156
Ratio CCTV	-0.426	3.838	6.649
Ethnic heterogeneity	1.182	7.139	11.527
Percentage retail and catering land-use	-0.395	17.054	23.084
Mixed land-use	-6.928	-3.196	2.428
Socio-economic status	-0.565	-0.233	0.188
Streetlighting density	-0.00126	0.00018	0.00159
Population density	-0.00019	0.00011	0.00049
Address density	-0.00060	0.00041	0.00083
Vacancy rate	-0.014	0.081	0.160
Local R-squared	0.617	0.728	0.909

Table 6: Results GWR violent crimes model. R2-adjusted: 0.803; AICc: 412.99

The intercept appears to have the highest coefficient in the southern part of the city, except the south-east region (Figure 3b). The city centre still has a relatively high coefficient whereas the rest of the city has a coefficient of zero or a negative value. The percentage of retail and catering land-use is the highest in the south-east region and the city centre (Figure 3c). The city centre having a relatively high coefficient seems logical, as the city centre experiences most violent crimes and the other variables seem to have less influence in the city centre. Ethnic heterogeneity seems to be influencing violent crimes most in the west, where a high level of ethnic heterogeneity can be observed (Figure 3d). It is interesting that the southeast region, which also has a high level of ethnic heterogeneity, has a relatively low coefficient. Remarkably to see is that ethnic heterogeneity follows a pattern that is similar to that of the local R-squared values. The coefficient for ethnic heterogeneity is the highest in areas where the R-squared is low. Address density has the highest coefficients

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in a few neighbourhoods in the far west, whereas the city centre also has a relatively high coefficient (Figure 3e). This makes sense as the literature shows that more urbanised areas experience more crime.

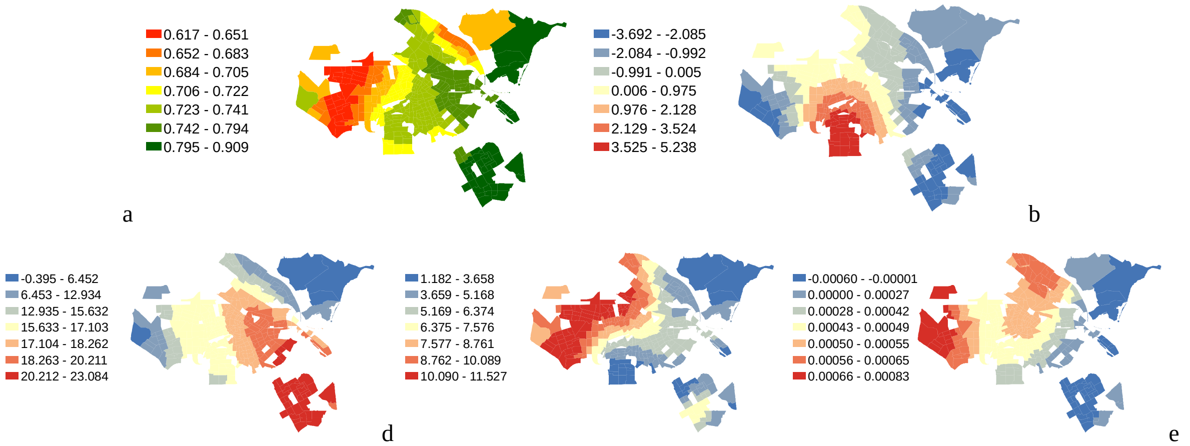


Figure 3: Maps representing results GWR violent crimes model (a) Local R-squared values; (b) Coefficients intercept violent crimes model; (c) Coefficients retail and catering land-use violent crime model; (d) coefficients ethnic heterogeneity violent crimes model; (e) coefficients address density violent crimes model.

5.2.4 Drugs and Nuisance

The GWR results for Drugs and Nuisance related crimes are summarised in Table 7. It is remarkable that there are no signs of improvement by taking spatial relationships into account. Hence, it could be argued that drugs and nuisance related crimes have stationary relationships with the variables included. However, a look at the variables individually shows that varying relationships can be observed.

	Lowest	Mean	Highest
Intercept	-1.653	0.029	2.393
Intersection density	-0.009	0.004	0.012
Parking density	-0.00077	-0.00047	0.00031
Ratio CCTV	0.944	5.138	18.458
Percentage retail and catering land-use	0.705	18.331	31.537
Tourist attraction density	-0.063	0.095	0.267
Streetlighting density	-0.00036	0.0002	0.00122
Population density	-0.000019	0.000065	0.00029
Percentage rented homes	-0.015	0.015	0.049
Vacancy rate	-0.023	0.068	0.118
Local R-squared	0.453	0.721	0.840

Table 7: Results GWR drugs and nuisance model. R2-adjusted: 0.732; AICc: 2137.37

The local R-squared values show that the model explains variance in the south-east region and the city centre the best (Figure 4a). This is preferable as most crimes occur in these areas. The intercept has the highest coefficient in the south-eastern part of the city (Figure 4b). The coefficient of the intercept for the city centre, where most drugs and nuisance related crimes occur, is close to zero. Hence, it could be argued that the variables in the model predict these types of crime well. The tourist attraction density has a relatively low coefficient in the areas where there are more tourist attractions (Figure 4c). Like in the vandalism model, it is expected that this is due to the high number of tourist attractions in the city centre compared to the other areas of the city. A high coefficient would probably result in extreme overpredictions. It is interesting to note that the coefficient for the parking density is negative in the areas where drugs and nuisance related crimes occur most (Figure 4d). A similar pattern as with the violent crimes model can be observed. Arguably, this is due to the fact that these crimes occur most in the city centre where the least parking places are present and thus parking is of less importance. Another remarkable aspect is that in the western part of the city, the coefficient becomes positive, which could be explained by the fact that there are relatively more parking places there, which has a negative influence on the principle of access control from CPTED.

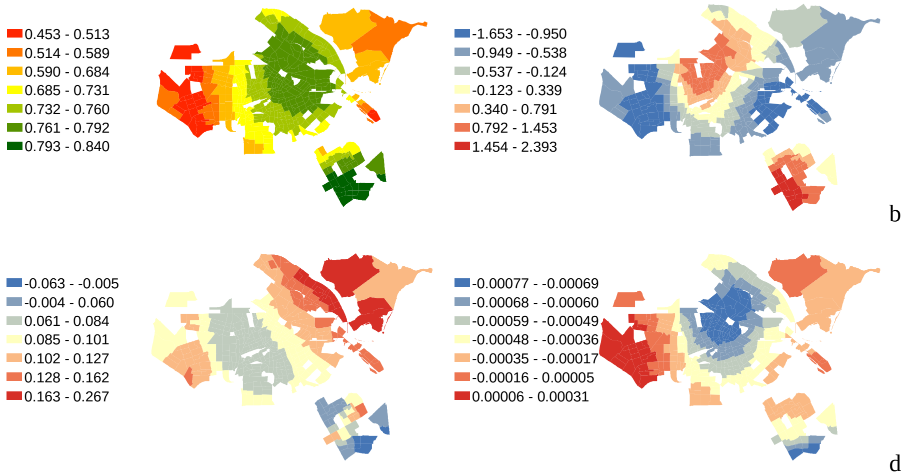


Figure 4: Maps representing results GWR drugs and nuisance model (a) Local R-squared values; (b) Coefficients intercept drugs and nuisance model; (c) Coefficients tourist attraction density drugs and nuisance model; (d) coefficients parking density drugs and nuisance model.

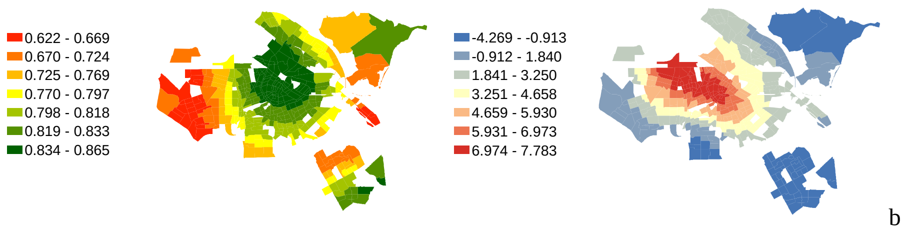
5.2.5 Theft

In Table 8, the coefficients obtained from the GWR for the theft model are displayed. Only a limited improvement can be observed when taking spatial relationships into account. From looking at the local R-squared values it becomes clear that the variance is best explained in neighbourhoods near the city centre (Figure 5a). This makes sense as most theft related crimes occur near the city centre, especially pickpocketing which is generally speaking near tourist attractions.

	Lowest	Mean	Highest
Intercept	-4.269	3.677	7.783
Ratio CCTV	-1.852	4.662	17.415
Percentage retail and catering land-use	3.221	23.616	30.033
Mixed land-use	-7.051	-3.018	3.251
Tourist attraction density	-0.302	0.126	0.278
Socio-economic status	-0.194	0.327	0.762
Streetlighting density	0.000	0.001	0.003
Population density	-0.00017	-0.000096	0.00019
Address density	0.00022	0.00048	0.00120
Percentage rented homes	-0.023	0.018	0.073
Vacancy rate	-0.044	0.147	0.319
Local R-squared	0.622	0.795	0.865

Table 8: Results GWR theft model. R2-adjusted: 0.824; AICc: 2298.92

The intercept has the highest coefficient in the city centre, whereas the peripheral areas of the city have the lowest coefficients (Figure 5b). Taking into consideration that the improvement of the GWR model in comparison to the OLS model is quite poor, it could be argued that theft is stationary, and that the intercept of the GWR acts as a measure of distance to the city centre. Tourist attraction density has surprisingly a relatively low coefficient in the city centre where most tourist attractions are present (Figure 5c). Arguably, this is due to the big differences in the values of the tourist attraction density of the city centre compared to the rest of the city. The highest coefficients for retail and catering land-use can be found in the city centre (Figure 5d). In this area, most land is covered by retail and catering facilities. This implies that the effect of retail and catering facilities is amplified in GWR analysis.



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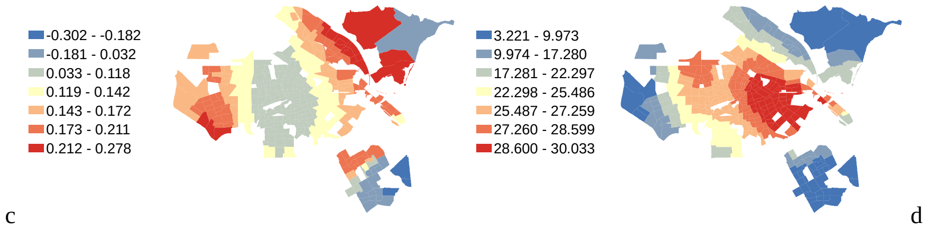

Figure 5: Maps representing results GWR theft model (a) Local R-squared values; (b) Coefficients intercept theft model; (c) Coefficients tourist attraction density theft model; (d) coefficients retail and catering land-use theft model.

5.2.6 Combined Crimes Model

Finally, all crimes combined were analysed. The results are displayed in Table 9. Taking spatial relationships into account was expected to result in a better model fit. Whereas an improvement of approximately .03 in the adjusted R-squared value might seem marginal, it should be noted that the adjusted R-squared of the OLS regression was .877, hence there is less room for improvement. Moreover, the AICc is more than 2000 lower than the OLS regression model.

	Lowest	Mean	Highest
Intercept	-2.621	6.734408	17.414023
Tree density	-0.003	-0.001	0.003
Ratio CCTV	0.658	7.357	21.990
Ethnic heterogeneity	0.016	8.443	17.185
Percentage retail and catering land-use	22.614	55.477	64.419
Mixed land-use	-12.564	-7.541	1.610
Tourist attraction density	-0.478	0.194	0.891
Socio-economic status	-0.245	0.553	1.083
Streetlighting density	0.0013	0.0026	0.0046
Address density	0.0011	0.0016	0.0036
Percentage rented homes	0.006	0.042	0.126
Local R-squared	0.799	0.864	0.942

Table 9: Results GWR combined crimes model. R2-adjusted: 0.916; AICc: 555.92

As can be seen, the areas with highest crime rates also have a higher local R-squared value (Figure 6a). It is preferable that the R-squared is highest in areas with the highest crime rates, as the upmost part of the total crimes are explained by the model.

The intercept appears to have the highest coefficient in the city centre, where relatively many crimes occur (Figure 6b). Arguably, the intercept compensates for variables which are not included in the models. A coefficient for the intercept of approximately 15, in combination with the square root transformation suggests that the intercept compensates for more than 200 crimes per square kilometer per year in those areas. Mixed land-use has the highest coefficients in the east of Amsterdam; towards the west the coefficients decrease (Figure 6c). When looking at the coefficient for the tree density, it can be observed that the city centre has negative coefficients, whereas the peripheral areas have coefficients near zero or positive ones. This implies that in those areas the tree density does not seem to reduce crime as much as in the city centre (Figure 6d). Tourist attractions density again follows a pattern in which the city centre, with most tourist attractions, has a relatively low coefficient (Figure 6e).

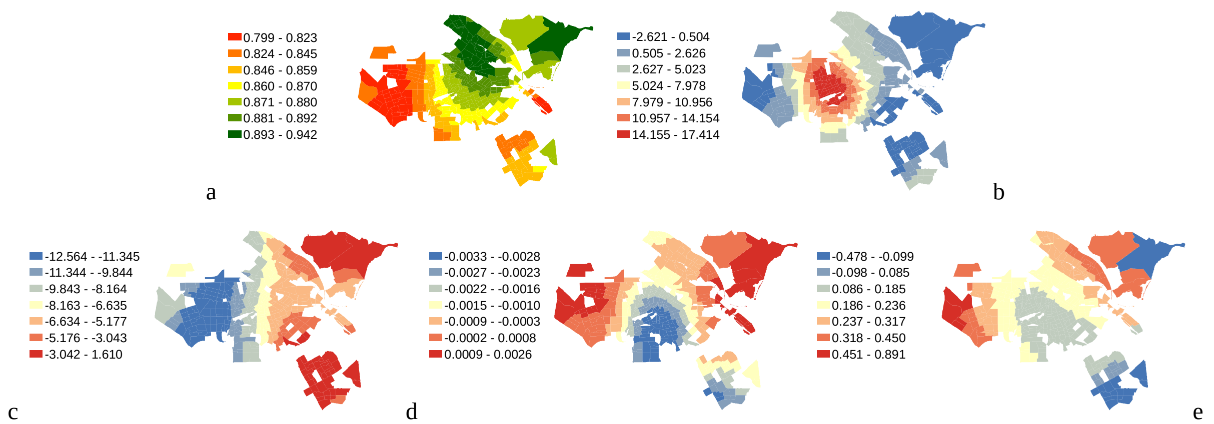

Figure 6: Maps representing results GWR combined crimes model (a) Local R-squared values; (b) Coefficients intercept combined crimes model; (c) Coefficients mixed land-use combined crimes model; (d) coefficients tree density combined crimes model; (e) coefficients tourist attraction density combined crimes model.

6 DISCUSSIONS AND CONCLUSIONS

In this research, multiple crime types were researched in regard to their relation to characteristics of the built environment and some regarding the social disorganisation theory as control variables. Firstly, existing literature was consulted to obtain the most relevant theories and contributions on this matter. Per crime type an exploratory regression analysis was performed to obtain the most suitable OLS regression model. Finally, a geographically weighted regression analysis was performed to obtain local variations in the relations between characteristics of the built environment and crime.

As regards the CPTED principles, in this study, some confirming findings can be observed. The number of intersections increasing crime is in line with the CPTED principle of access control, as the number of intersections increases the permeability of the neighbourhood and thus weakens the access control. Mixed land-use should act as a measure to improve natural surveillance, which it does as all the signs are negative. The vacancy rate is also in line with CPTED, namely the image and milieu principle. As vacancy is argued to have a negative effect on the image of the neighbourhood, resulting in more crime. The vacancy rate is positively correlated with drugs and nuisance related crimes, violent crimes and theft. The number of rented homes, arguably, can be seen as a negative measure of territoriality, as people are more inclined to defend their own property. The percentage of rented homes is positively correlated with drugs and nuisance related crimes, theft and crime in general. Hence, variables representing all CPTED principles are in line with the CPTED strategy. However, there are also some variables which are not found to be reflecting the CPTED strategy. CCTV for example, which should act as a measure of surveillance and access control, however, shows a positive correlation. The same goes for the streetlighting as a measure of natural surveillance, artworks as a measure of territoriality and parking places as a measure of access control.

When taking spatial relationships into account, it can easily be observed that for burglary, vandalism, violent crimes and crime in general the models improve significantly. Drugs and nuisance related crimes as well as theft seem to have a limited, if any, improvement. Hence, it could be argued that drugs and nuisance related crimes and theft are stationary as there were no significant model improvements when considering spatial relationships. Moreover, taking into account spatial variation of the coefficients provides the opportunity to observe where certain variables are more influential and where they are not.

As regards to policy making to decrease criminal activities in the city centre of Amsterdam, it could be argued that due to the high number of tourists and retail and catering facilities, that the number of pedestrians is already sufficient to provide natural surveillance. On the other hand, as Angel (1968) suggested, the number of potential victims also increases with a high land-use intensity [50], which is evident of the case in the city centre of Amsterdam. Hence, formal surveillance is more recommended rather than measures which increase natural surveillance. Measures such as limiting retail and catering facilities could help reduce crime, but would have negative economic consequences. Concerning tourism, it is recommended to evaluate whether the benefits of the high number of tourists outweigh the disadvantages such as crime, but also the deterioration of the city centre, social and environmental sustainability issues and the nuisance in general that the residents of Amsterdam experience. Limiting the number of tourists could be done by implementing a higher tourist tax or by regulating the number of hotel rooms and short-stay rental platforms.

Concerning other areas of Amsterdam, it is recommended to implement more diverse land-uses in its neighbourhoods, as the results of this study show that this might beneficial in reducing crime. Mixed land-use will in turn also lower the population density, which stimulates crime, as multiple functions besides residential are present in the area.

In general, it can be concluded that the built environment does have an influence on the occurrence of crime and that this influence differs among crime types. Moreover, different characteristics of the built environment influence different types of crime. It should be stated that there is consistency in variables between crime types, i.e. the percentage of rented homes and the vacancy rate are consistently positively correlated in all models in which they were included. Further research is recommended to increase the knowledge on the influence of the built environment on crime and to do this for multiple contexts and levels of analysis to get a more thorough understanding of this matter. Moreover, it is recommended to consider

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spatial statistics more often, as it could increase general model performance and help understanding local differences, however, this requires the availability of spatial data.

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