SPRAWL AND DISTANCE TRAVELLED: EVIDENCE FROM EUROPEAN METROPOLITAN AREAS

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DECLARATION OF AUTHORSHIP

I, Amon Boontore, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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ABSTRACT

The fact that populations tend to agglomerate in urban areas during a time when world population is increasing and cities are exerting an ever greater pull on migrants makes city growth management one of the most challenging issues the world needs to confront. The urban phenomenon which has been called 'sprawl' for over a century has been identified as causing various key problems e.g., loss of resource land, amplifying dependencies on the automobile, generating air pollution, and so on. However, there is controversy, even amongst scholars, surrounding the advantages and disadvantages of this phenomenon since there is no common agreement principally on the definition and characteristics of sprawl. This research was sparked by the idea that measurement is a significant step to gaining knowledge of the fundamental structures and processes at work in city systems which generate sprawl. The main purpose of this study was to create an aggregate sprawl index using distance travelled made by private motorised vehicles as a proxy for sprawl, and taking European metropolitan areas as case studies.

With respect to independent variables, quantitative characteristics of land-use patterns in relation to sprawl were developed across eight operational dimensions primarily using concepts from landscape ecology. Twenty-three indicators according to these dimensions were reviewed. Then, numerical data on land area, perimeter and distance were extracted from the land cover maps of various European metropolises, and used in calculating the aforementioned indicators principally using MATLAB© scripting. In identifying the most suitable indicators for each operational dimension of sprawl, various criteria were applied, including stability tests of these indicators.

Finally, multiple linear regression analysis was employed to model sprawl. As a result, a linear regression model of urban sprawl for these metropolitan areas was formed using a single independent variable, the eta squared index (ETA), which is characterised by a mixture of land uses, thus introducing the concept of 'exposure'. This model is capable of explaining 32.5 percent of the total variation of the degree of sprawl with respect to private motorised vehicle distance travelled. Complemented by the model's effect size

index which is also measured by Cohen's f^2 statistic (with a value of 0.48) gives some confidence in the variables that have been identified in this study and which form the basis of the exposure index.

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CHAPTER 1: INTRODUCTION

In this introduction, the context of this thesis is described through empirical statistics which relate population growth at the macro scale to the issue of increasing resource consumption, particularly land which is best expressed in the form of city expansion. We also specify the problem area and define the main aims of this research. The research propositions and hypotheses are presented, and then the research methodology is delineated. We conclude this introduction with an outline of how the thesis is organised and note the limitations that any study such as this has to meet.

1.1 BACKGROUND OF THE STUDY

The total land area of the earth occupies rather less than 1/3 of the earth's surface, a little more than 14,000 million hectares or 140 million square kilometres (United Nations Environment Programme (UNEP) 2002). Counting both developable and undevelopable land areas, around 4 percent of the global land surface or more than 471 million hectares is occupied by built-up or urban areas (World Resources Institute 2000). Approximately three billion people or half of the whole world's population will now live in these urban areas and it is projected that almost all the world's population live in urban areas by the end of this century (World Resources Institute 2000). People tend to agglomerate in cities due to their driving forces i.e., better services and opportunities reflecting their economic prosperity, education, employment and the health facilities that are offered centrally. These define economies of agglomeration.

Cities play a vital role not only as suppliers of shelter, jobs, facilities and services, but also as centres of social interaction, culture, technological development, and industrial centres for processing and manufacturing various kinds of products. Even towns and cities occupy only a few percent of the land surface, but their demand for food, water, natural resources, and location for waste disposal and treatment dominate the environment around them. With proper management, cities can also become both an opportunity and a solution for securing a better future in terms of living conditions. In conjunction with the importance of land which is one of the most delicate resources in utilizing it in cities, urban areas obviously appear to have the most potential for generating prosperous urban futures.

In *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*, which used a world model focussing on resources limits and capacity, Meadows *et al* (1972) investigated five main global concerns including industrialization, swift growth of population, extensive undernourishment, depletion of non-renewable resources, and a decline in the quality of the environment. Their results suggested that if the growth trends of the 1970s continue at the same exponential rate as before, the earth will reach her capacity limit within the next coming century. The world population in 1950 was 2,529,000 (United Nation: Department of Economic and Social Affairs 2008). From 1950-1975, human population increased roughly 61 million per year and approximately 81 million per year from 1975 to 2009 (United Nations: Department of Economic and Social Affairs: Population Division 2009). Even the birth rate has declined in this worldwide picture but the global population has risen annually by about 80 million. This growth trend will continue. An adjunct to this escalation in world population can be explained by the decreasing global mortality rate (World Resources Institute 2000). World population growth interplays with the pulling and agglomerating forces of the city, and both factors drive the pressures on urban areas to get ever larger.

The first Industrial Revolution began approximately in 1750, first in Britain and then spread into Europe, followed by North America, and finally in the last century it influenced the entire world. By 1900 Great Britain was the only country in the world that could be considered as an urbanised society with more than half of its population living in urban areas (Zeigler et al. 2003). At that time, industrialised cities were occupied by factories and low-quality housing leading to variety of environmental problems such as poor sanitation, air pollution, housing shortages and overcrowded dwellings particularly in the central city. Consequently, the main reaction to attack these issues theoretically and practically were grounded in decentralisation and reducing the density of the city. Modern urban planning actually began to develop in Britain around 1850 in order to react to these negative impacts of the industrial revolution which were especially rooted in massive densities in the central city. In European cities after the period of the first Industrial Revolution, the significant role of the city (Jenks et al. 1996) in terms of the focus on policies or practices to improve city living and to reduce densities gave added impetus to urbanisation and the design of a better quality urban environment. Urban planning, particularly in the developed world, evolved right the way through the 20th century generating a plethora of urban forms where there was little concern for their wider social, economic and environmental effects, and one of the most widespread and distinctive forms of urban development during that period came to be defined as *urban sprawl*.

In 1987, the World Commission on Environment and Development (WCED) published *Our Common Future*, also known as *Brundtland Report*, and this was regarded as one of the most influential environmental statements on urban life and resource limits in the twentieth century. It investigated various important issues threatening and challenging the global future including population and human resources, food security, species and ecosystems, energy, industry, and the urban challenge (World Commission on Environment and Development 1987). The content of the report urges humanity to reconsider and raise awareness of the impact of their development actions on the planet they are living in. The report has awakened public concern about environmental problems and expanded awareness and responsibility into almost every discipline, generating a global agenda in pursuit of *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (World Commission on Environment and Development 1987). Moreover, it has extensively brought to the fore and enlarged the issue of the way human beings settle their environments. In other words, it has posted challenging questions about the ideal urban forms that might meet the goals of sustainability and resource conservation that are clearly needed as world population continues to grow and as an ever larger fraction of the world's population live in cities.

In fact, in the past, many diverse ideas have been proposed in order to create ideal city forms that can maximise inhabitants' living conditions in terms of social and economical benefits while minimising environmental damage. One famous example is Ebenezer Howard's *Garden City*. In modern times, one of the most notable arguments about urban form appeared in 1997 when the journal *Environment and Planning B* published the so-called first debate between two diametrically opposed proponents of different urban form based on compact versus sprawl development (Ewing 1997; Gordon & Richardson 1997). These terminologies immediately imply contradictory notions. Moreover, this debate clearly stresses that the concepts lying behind those two types of urban form exist at completely opposite poles of opinion, an issue which has continued to be debated in later studies and shows little sign of subsiding. It can be said that currently the debate between the compact city and urban sprawl polarises this question of urban sustainability and as such its understanding represents one of the basic motivations for this thesis.

1.2 PROBLEM STATEMENT AND RESEARCH AIM

The origins of this research can be formulated by the expression: *The way we live determines our future*. Additionally, in our concern for developing sustainable urban development, the main question that this research poses stems from the question of "What is the better urban development choice between the compact city and urban sprawl?" Prior to answering such a generic question, our understanding of such urban phenomena must be clarified; and in this quest, measurement is a vital primary step in supplying knowledge about underlying structures and processes (Lam & Cola 1993) which function in city systems.

This research attacks the problem through scrutinising urban sprawl rather than exploring the idea of the compact city due to the fact that sprawl is an urban phenomenon with an intriguing history and also tends to dominate the kinds of cities that have been developed over the last 100 years or more. Therefore, the main question of this research lies in how urban sprawl can be measured. Congruent with this research question, this research poses two main objectives which are implemented as follows:

1) To autopsy urban sprawl and reveal its main characteristics as developed using various quantitative indicators

2) To create an aggregate model of urban sprawl that can estimate the degree of sprawl as a static urban phenomenon, taking a wide sample of European metropolitan areas as case studies.

It is important to emphasise that general profiles about sprawl including the issue of its history, causes and consequences will be investigated and discussed in relation to the research objectives of searching for some quantitative aspects of sprawl rather than attempting to pursue and understanding of the forces of urban growth and development for their own sake.

1.3 RESEARCH PROPOSITIONS AND HYPOTHESES

Aiming to meet the objective of creating an aggregate model of sprawl, this study basically works with the subsequent propositions:

1) Sprawl is a matter of degree, so it must be measured quantitatively across a range of indicators and,

2) Sprawl is a multidimensional phenomenon, not just defined as low density development, although it can be best defined in terms of its residential aspects.

This research assumes that sprawl has strong links to urban growth and expansion in two-dimensional space where public transport facilities and services are much more decentralised from those in the centre of the city. The expansion of the city implies increasing dependency on private vehicles due to the fact that travel is a derived demand and one of the most dominant activities taking place in a metropolitan area.

Thus, this study hypothesises and uses the distance travelled made by private motorised vehicles as a proxy for sprawl, while the characteristics of land-use distribution in relation to sprawl phenomenon will stand on the other side of our models as independent variables explaining the forces that govern how sprawl takes place. The discipline of landscape ecology is applied to establish these spatial traits of sprawl. Two-dimensional land cover maps will be used as the main source, which provide spatial information through polygons of different land uses, in estimating the characteristics of land-use distribution in relation to sprawl. It should be noticed that the first proposition allows us to reflect aspects of the compact city in terms of low degrees of urban sprawl which enables us to consider degrees of compactness and examples of urban development, albeit few that there are, which are close to the idea of the compact city. Finally, this study further hypothesises that the degree of sprawl derived from its characteristics linearly correlates with the distance travelled made by private motorised vehicles.

In the mid-1990s, the World Resources Institute calculated the remaining amount of the three main energy resources based on fossil fuels including coal, petroleum and natural gas. Based on the prevailing economic conditions, technological advancement and re-estimation of existing reserves and the unearthing of new reserves, the verified reserves could supply coal needs for 200 years, natural gas for 50 years, and petroleum for 40 years (World Resources Institute 1994). Accordingly, using the distance travelled as a proxy for sprawl, which links to the issue of energy consumption since most trips making basically rely on fossil fuels particularly petroleum products or oil, this allows us to frame this research in way that will discover the factors that determine sprawl, thus enabling us to define the relative importance of these resources to these issues.

1.4 Organisation of the Thesis

This thesis is organised in seven chapters. Chapter 1 presents a general introduction to this thesis, including research questions and our main aims. Chapter 2 focuses on deriving the quantitative characteristic of sprawl which works with the review of the previous works attempting to measure sprawl. In Chapter 3, we develop the conceptual and operational dimensions of sprawl. Then, potential indicators that can be employed to estimate each operational dimension of sprawl will be examined in Chapter 4.

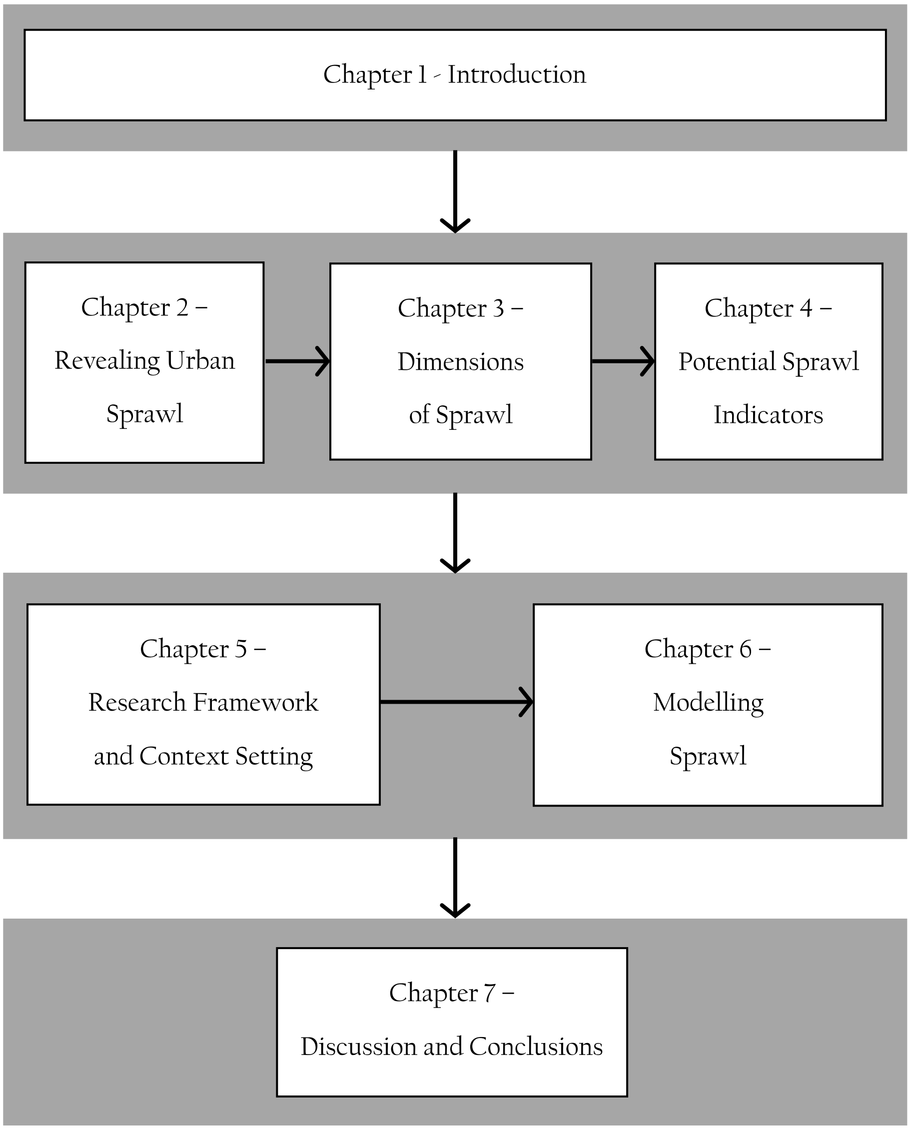


Figure 1.1: Thesis organisation

The research framework and methodology describing each main step that leads to the construction of the model of sprawl is presented at the beginning of Chapter 5, and then we specify the unit of analysis, the case studies of European metropolitan areas and the transport data used in this study in Section 5.2 and 5.3, respectively. Various conditions, especially the stability tests, are applied to identify the most suitable indicators for estimating each conceptual dimension of sprawl (Section 6.1 and 6.2) where all the calculated indicators are presented in Appendix F, G, H and I. Multiple regression analysis will be used in constructing the sprawl model (Section 6.3). Finally, findings from the results are discussed and general conclusions are drawn in Chapter 7. Figure 1.1 provides a schematic representation of the organisation of this thesis.

CHAPTER 2: REVEALING URBAN SPRAWL

In order to understand urban sprawl, our argument basically requires knowledge in at least five different areas: 1) definitions, 2) causes, 3) characteristics, 4) consequences and 5) measurements. As the overall aim of this thesis is to create a model of urban sprawl, the most important component that we will emphasise is finding a way to calculate the degree of urban sprawl and this clearly involves data, analysis and the construction of indicators. However, delineating the definition and characteristics of urban sprawl provides a more straightforward link to urban sprawl indicators rather than a focus on purely investigating its causes and impacts, although we will of course pursue the latter as part of our argument.

The terminology *sprawl* is one of the words that is now widely used in the urban planning realm at present, particularly in the context of rapidly growing cities and cities that are fast restructuring around the development of new forms of automobile transport. But looking back at the key history of the term is worthwhile for this presents a proper start in getting to understand urban sprawl in its most thorough sense.

2.1 A HISTORY OF URBAN SPRAWL

Urbanisation is a process involving the migration or movement of peoples and changes in their lifestyles that stem from living in new environments, particularly the movement from the countryside to the city but also between regions and nations more globally. The term urbanisation provides is a big umbrella that covers many topics concerning urban phenomena including urban sprawl, and thus we will begin by exploring urbanisation as this will provide a comprehensive understanding in setting the context to the emergence of urban sprawl.

2.1.1 Trends in World Urbanisation

The first period in which we can recognise early urbanisation dates from pre-history or the distant past to about the 5th century. The first cities in human history were located in Mesopotamia emerging about 4000 BCE, in the Nile Valley about 3000 BCE, in the Indus Valley by 2500 BCE, in the Yellow River Valley of China by 2000 BCE, in Mexico, and in Peru by 500 CE. On average, the population of these ancient cities did not grow much and their populations stayed in the range of 2,000 to 20,000 for the first thousand years or so of their existence (Zeigler et al. 2003). Rome ultimately became the largest ancient city and was estimated to hit a population of about 1 million in the 2nd century CE. One of the most distinctive features of these ancient cities was that trade was a basic function linked to their surrounding areas or hinterlands and providing rudimentary links to other cities. Each ancient city normally grew from the farms, villages or small towns that supported the agricultural landscape, forming key points of distribution for a wider hinterland.

After the fall of Roman Empire, urban nodes became isolated from one another in order to survive through the European Dark Ages. The collapse of Roman Empire in the 5th century CE led to a decrease in urbanisation with the main reason for this diminution being seen in considerably less spatial interaction between populations due to a decline in trade. After that period as the world recovered from these Dark Ages, trade-related activities between city and rural areas and among other cities were the chief factors in the increasing size of the city. However, such interactions were continually interrupted by deterioration of the Roman transportation system, the spread of Islam from 700 to 800 CE, and the plundering raids of the Norse in the ninth century. All of these trends ultimately led to rural and urban population shrinkage with isolated inhabited regions becoming the norm although the seeds were gradually set for a revival in Europe.

Although fortified urban settlements and clerical centres did emerge in the eleventh century when the so-called Middle Ages began, social interactions were limited to the immediate surrounding areas. Consequently, growth in population and in cities remained extremely small with the population spending most of their lives within the walls of the city. In due course, the enhanced role of commerce resulted in the emergence of mercantile policy throughout the European continent and thence the Renaissance of culture began and the early modern period saw the revival and growth of cities. History suggests that government played a protectionist role in the economy by promoting exports and discouraging imports through the use of taxes and subsidies. The main idea of mercantilism was to protect the merchant which became the new social middle class, through the establishment of trade monopolies, the supervision of financial support, and military defence of the commercial interests of the nation. In this period which began in the 15th century in Italy, cities served as commercial and economic centres (Zeigler et al. 2003). However, the nature of the merchant class and industrial capitalism based on maximising profits drove the merchant classes to resist economic laws as they began to use their increasing financial powers to claim liberty from the control of the state. Eventually, this led to an end to mercantilism. The new capitalism broke down the remnants of the feudal system and formed new functions for the city which came to be known as industrialisation. The Industrial Revolution thus began and with it, new technologies largely of movement meant that cities could begin to grow to sizes that hitherto had been simply impossible to reach.

At the same time when Europe experienced death and then the regeneration of its cities, other non-western civilisations did not undergo the same pattern largely due to differences between their political, cultural and geographical contexts. Even if some empires such as the Chinese passed through turbulent economic times, their cities, especially in Asia and the Middle East, were able to maintain their role as political, cultural, religious or commercial centres. Nevertheless, urban evolution in Sub-Saharan Africa and Latin America i.e., the Mayan, Incan, and Aztec civilisations, were annihilated by Western colonisation. Subsequently, new cities which reflected European culture were created on top of these eradicated cities. The European-inspired city idea became a model for urban development throughout the known world which we pursued through the establishment of colonial empires after the fifteenth century. In

North and South America and Oceania, Western colonisation demolished native cultures and cities while co-existing with and transforming indigenous societies in most of Africa, Asia and the Middle East (Zeigler et al. 2003).

2.1.2 THE AGE OF INDUSTRIAL EVOLUTION

The Industrial Revolution is the crucial turning point in human history that changed the face of world urbanisation. Gaining huge advantages from the colonial expansion of the 17th century, the United Kingdom was one of the most affluent countries from its agglomeration of natural resources from numerous overseas colonies such as its West Indian plantations, the slave trade between Africa and the Caribbean, and related exploitation. Along with the formation of financial markets and the agglomeration of capital that brought about the technological revolution, major changes in agriculture and manufacturing production posed an intense effect mainly on the socioeconomic structure of western society, beginning in the United Kingdom and spreading throughout Europe, North America, and finally to the rest of the world through the name of the Industrial Revolution.

The first phase of the Industrial Revolution roughly began between 1700 and 1780 in parts of Great Britain. The move from manual labour and the draft-animal-based economy towards a machine-based economy, especially with the mechanisation of the textile industries and the development of iron-making techniques began the revolution. Major heavy industries were located out of the traditional pattern of towns and in countryside around key resources locations where iron ore and coal was to be found, thus establishing a new pattern of urbanisation. Increasing reliance on refined coal instead of water power as a main raw material used in industry encouraged the concentration of industry where coal could be made mined and many new towns developed from scratch or from small villages in Lancashire, Yorkshire, Durham and Staffordshire (Hall 2002).

After the introduction of the first steam-powered railway in 1825 as one of the key elements based on the internal combustion engine, which lead to the second phase of the Industrial Revolution, industry became more footloose and began to concentrate in new forms of settlement: the industrial town. Some of these development were situated in pre-existing cities (Gillham 2002), in Medieval cities in the case of Leicester, Nottingham and Bristol, for example (Hall 2002) due to easy accessibility to coalfields or railway intersections; while from the 1780s onwards, various new industrial towns were generated, and some the earlier port cities such as Liverpool, Hull, Glasgow and London became ever more geared to manufacturing industry (Hall 2002).

When workers from the agricultural sector were transformed to be industrial workers, they located themselves in areas that had massive new demand for labour resources required by the factories. The factories were agglomerated around and inside towns. This meant that urban areas grew much faster than other parts of the country because of massive immigration of peoples from the rural hinterland rather than simply through accommodating the natural increase in population (Benevolo 1980), notwithstanding that a large proportion of this population growth from the 19^{th} century onwards was due to declining death rates.

Wherever the factories were located, labour was attracted by higher incomes and better opportunities for their quality of life relative to farm life which for many hundreds of years had been stable but at subsistence levels. As the need for labour in the industrial sector expanded, more and more people moved to cities. The Industrial Revolution which led to this immense urban immigration exacerbated the physical problems of the city in terms of health and pollution (Gillham 2002; Mumford 1968). Mumford (1968) painted a vivid portrait of towns turned into 'dark hives', busily puffing, clanking and screeching, smoking for twelve to fourteen hours a day, sometimes around the clock. The newcomers crowded into whatever housing was offered. It was a period of vast urban improvisation with makeshift hastily piled upon makeshift. Although some said that this was far worse than the rural existence that many new urban dwellers came from, there was opportunity for the first time to break out of the rigid class system which was still largely based in feudalism of a kind. The enlargement of professions led to a sizeable middle class which emerged in newly industrialised countries especially in Europe. But even rich people and this new middle class spent their everyday life, more or less, in the same way as the poor in urban core which were crowded, polluted, and unhealthy. But gradually these urban elites found the way to escape from the urban poor and the unpleasantness of the central city by living outside of the city core and the suburbs that took them were directly made possible by the first mass transit, the development of trams and trains in the mid of late 19th century. This was the first stage of spatially detaching housing from the workplace and although initially it was only for the exclusive rich, it represents the beginnings of urban sprawl as we have come to call it today.

2.1.3 Railroad and Streetcar Suburbs

Inherited from the Middle Ages, small and dense cities that principally developed around walking-distance were often surrounded by walls or moats and normally bounded within five kilometres from one end to the other end. This form of city can be widely seen in the central part of old cities in Europe and occasionally in North America especially on the east coast. Clear and still-existing examples are shown in Figures 2.1 (a) and (b) and Figures 2.2 (a) and (b). The industrial city gradually evolved through the 19th century. It was the loud noise, dirty air and unhealthy urban environment of the industrial period that provoked the call for a new ideal: a return to the idyllic countryside, to the paradise garden-cottages located away from the unpleasant industrial cities. This of course led to the idea of the garden city which became, by the end of the 19th century, one of the key drivers for urban sprawl beyond the more compact industrial city that had developed during the first 100 years of the Industrial Revolution.

From this revolution, the scientific innovations and technological changes in transport and vehicle design in trains, trams and automobiles, and eventually in air transport brought vital changes to urban form. Together with the unpleasant conditions of industrial city, this became the trigger point leading to the *modern suburb* (Gillham 2002). It is true that suburbs, archaeologically evident in ancient cities in regions such as Mesopotamia and Egypt (Mumford 1968), had subsisted in these early cities themselves, but the modern suburb referred to here is significantly dissimilar to these ancient suburbs Mumford that refers to.

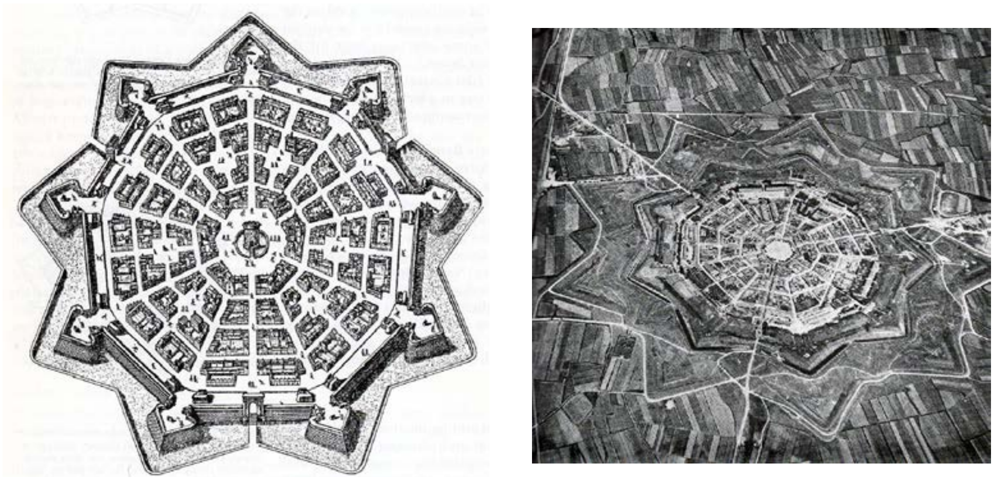
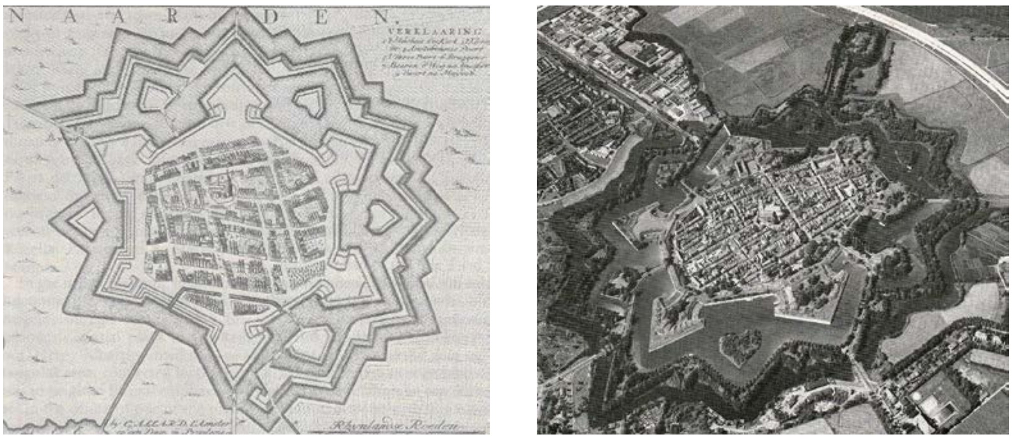
(a)  (b)

Figure 2.1: A planned town influenced by small and dense Middle Age cities: an ideal city plan designed by Vincenzo Scamozzi (1551-1616), an Italian Renaissance urban theorist (a); and an aerial photo of Palma Nova (b) (Morris 1994)

(a) 

(b)

Figure 2.2: Layout plan (a); and aerial photo (b) of Naarden, east of Amsterdam in the late seventeenth century (Morris 1994)

The mobile steam locomotive in the form of the internal combustion engine was patented by James Watt in 1806. The first public steam railway was built in 1825, while the technology of trams or streetcars first horse-drawn in the early of 19th century, later shifted to the use of steam and electric power. Trams were widely used throughout the industrialised countries in the late 19th to early 20th centuries but even they disappeared from most British, French and North American cities by the mid-20th century although they continued to be utilised in some parts of continental Europe. Through the long history of trial and error in introducing various modes of public transport like in Britain for example, did in trying steam coach, horse-bus, horse tram, battery bus, electric tram, steam bus and trolleybus, respectively (Duffy 2003), it was the development of passenger trams and trains in the latter part of the 19th century that really propelled the evolution of city form to the next step. Advances in transport development at this stage did allow the cities to expand their boundaries outwards beyond 20–30 kilometres (Newman 1992). This lead to a tripling in the areal size of walled cities (Gillham 2002) but it essentially led to cities growing to 1 million or more and then to cities expanding ever upwards in population with New York City reaching 10 million in 1970.

Trains created isolated enclaves around their stations while grid-based and ribbon development clung to the tram lines which followed radial routes out of town. The width of the ribbon and the radius of the pedestrian pockets were some part determined by walking distance from the rail line. Early versions of these railroad suburbs were designed for the rich, especially in the United States. The high density of various activities can be seen where the rail routes intersect with the city centre. Many European cities have been shaped by this pattern of development, albeit those transportation systems being relatively inactive at present. Electric transit led to the urbanised area encircling the city centre, thence engulfing the countryside at a rapid rate. Specifically, it was the speedy growth of the streetcar suburb that was blamed as the invader of the countryside.

2.1.4 AUTOMOBILE SUBURBS

The rate of growth that the streetcar contributed to urban expansion was small in comparison to what the automobile has done. The early automobile technology was developed from the scale-model toy in 1672, to a human-pedalled four-wheeled carriage, and three-wheeler in the 1750s and 1760s. It became more practicable when Richard Trevithick demonstrated his steam-powered road vehicle in 1801, even it failed to maintain enough steam pressure to make any long run. In 1881, a three-wheeled automobile powered by electricity was demonstrated for the first time at the International Exhibition of Electricity in Paris. Although many contributed to the development of automobile technology, Karl Benz is widely considered as the creator of the modern-day automobile with the establishment of his automobile company, Benz & Cie. in 1883. His first car controlled by a four-stroke cycle gasoline engine was sold in 1888. In fact, cars were firstly sold in small quantities in France by 1898 but mass-production of affordable cars was started by Ransom Olds in 1902 and his concept was dramatically enlarged by Henry Ford in 1914 in the city of Detroit. Though the prelude to the automobile age dawned between 1910 and the 1920s (Wheeler 2000), after the World War Two, private cars and public buses became the technology that shaped the city in such a way that, initially, the empty space between train routes defining the radial structure of the city was filled in. Cities then began to spread out to a radius of 50 kilometres or more (Newman 1992). People were freer to locate themselves away from high density activities and dense population in central business districts. Gillham (2002) speculated that Radburn in Fairlawn, New Jersey established in 1927, was the earliest formally designed auto suburb. Several innovations from Radburn i.e., pedestrians-car segregation, separate pathways, and a formally designed hierarchy of streets ranging from main arterial roads to cul-de-sacs, became the guideline for car based development throughout the United States (Gillham 2002). In the time of the streetcar suburb, isolated land between the rail lines could not be developed because of limited access but this was overcome by the arrival of the automobile. It allowed growth wherever there were roads or where roads could be built. Moreover, it decreased the cost of buildable land. This stage in urban evolution structured urban development over the past half a century and is still the predominant model of urban growth in many cities in North America, Australia and to an extent even now in China.

During that same period of Industrial Revolution, the great change in British agricultural production involved increasing efficiency in harvesting and producing food and this led to much less intensive human-labour being required. Previous factors interplayed with these trends such as better control of epidemics partly resulting from decreasing infant mortality rates, ultimately followed by continuing rural depopulation resulting in massive increases in population and labour force in industrial cities. The spiral of interaction between population growth and better development in production resulted in escalating populations with better goods and services, and these elevated living standards leading to increased demand for more plentiful and diverse goods and services, so on and so forth (Benevolo 1980). Finally, in the long term, these surplus workforce that remained in the countryside who could no longer find jobs in agricultural sector, were pulled by economic opportunities to the industrial and manufacturing sectors in the cities. Most people in fact settled themselves within walking distance of factories and this did lead to population density rising during the first half of the 19th century in terms of high persons per acre and per room (Hall 2002). London has displayed an extraordinary example of the growth patterns resulting from the Industrial Revolution doubling in population to 2 million between 1801 and 1851, doubling again to 4 million in 1881, and growing to 6.5 million in 1911 (Hall 2002).

Air and water pollution continued to provide a major problem in large cities mainly the results of coal burning. Water supplies were also contaminated by sewage. Not only did bigger cities but also many small villages that swiftly jumped to crowded towns had no proper management for water supplies, sanitation, garbage disposal system, and other provision for basic needs. Wastes from households aggravated the situation. Moreover, the better and larger mobility that resulted from the first type of commuting and an increasingly active and interactive economy meant that diseases could transport themselves faster nationally and even globally (Hall 2002). Cities became obscene and unpleasant places by the end of the 19th century clearly confirmed by the cholera pandemics in Britain in 1832, 1848 and 1866, and the severe pollution that appeared as the 'Great Smogs' that affected London as late as December 1952.

In conclusion, developments in technology since the late of 17th century led to the Industrial Revolution which marked an important turning point for the form of cities and urban evolution. This really became significant after 1870 with the expansion of urban boundaries in the form of increasing population densities within five kilometres of the centre where people could walk to their workplaces within one hour. This was caused poor transit systems at that time. In 1851, London, the biggest city in Europe at that time, doubled her population to two million within 50 years with a radius out only to 4.8 kilometres. It should be noted that unlike the Medieval Age where cities which had a clear boundary like the wall or moat, it was the area with the significant density of population which was considered as the proxy for the definition of the city. The wide use of horse trams and buses after 1840, electric trams after 1900, and motor buses by 1914 were evidence of the availability of more efficient public transport systems. Afterwards, cities noticeably expanded in many directions (Hall 2002). In the years between the First and the Second World Wars, decentralisation was instigated by interplay of social, economic, and transportation technologies. The electric trains and motor buses made expansion of cities like London possible up to five times their radius largely because new forms of transport were able to move people five times faster than walking (Hall 2002).

Suburban areas were the only solution that allowed people to escape from the crowded and polluted central city where the rapid growth that induced great changes to their physical structure had turned them into unpleasant places to live (Gillham 2002; Mumford 1968). Trains let cities expand further than the populations walking abilities and these evolved into small pockets of development around stations while more continuous-linear developments were developed in the case of trams. Relatively, the physical structure of the city significantly changed when mass production of affordable cars became available in the early 20th century. These private modes of transportation made the absolute separation of home and workplace possible for the first time and it was between the World Wars in the United States that this became the conventional reality.

The era of the automobile was not the sole factor that led to the rise of urban sprawl. Other factors such as governmental policies in housing provision, financial-aid programmes and subsidisation in road and highway construction and improvements after the Second World War, also played a part in providing opportunities for people to live anywhere they wanted to, especially in a dispersed style (Andres et al. 2000). Another vital factor was urban planning instruments, especially the concept of zoning. The discipline of town planning was formulated in order to react to European and North American urban problems in the 19th century, mainly resulting from the Industrial Revolution. In 1916, zoning was applied for the first time in New York City with the purpose of bringing back clean air and lighting to the industrial city. The main idea of zoning was to spatially separate industrial zones, factories and rail yards, from residential zones, houses and apartments (Gillham 2002), and this was as large as the main way of organising land use plans by the mid-20th century in many western nations.

Somehow, certain zoning plans i.e. the Regional Plan for New York and its Environs in 1929, widely brought about regional transport routes such as highway systems which gave way to suburban developments and dispersed industrial land use from city centres (Wheeler 2000). This made populations more dependent on automobiles than ever. Moreover, it was the inefficiency of planning that ignored the consumption of rural land by the city. In the case of England and Wales, through the Acts of Parliament in 1909, 1925 and 1932, powers were given to local authorities to make their own town plans but these acts did not provide any powers to stop development that was not in public interest (Hall 2002). So, generally, real-estate developers could build more or less anywhere they wanted to. This pattern of development has been applied intentionally and unintentionally since the late 1920s.

The final important factor worth mentioning is the post-Second World War planning system. During the mid to late 1930s, Britain began to recover from the Great Economic Depression of 1929-1932; however, certain regions which had been among those worst hit, particularly the older industrial areas, were not improving at a similar speed to the rest of the country (Hall 2002). Increasing differences between the prosperity of the South and Midlands, and continuing despair in the North, Wales and Scotland was one of the strongest voices that called for a large-scale economic development type of planning helping to connect the development of each region to the progress of the national economy. Moreover, growing unemployment rates and large-scale migration from the depressed areas in Great Britain forced the government to take action, and in 1937, a Royal Commission on the Geographical Distribution of the Industrial Population under the chairmanship of Sir Anderson Montague-Barlow was appointed to investigate the problem comprehensively and to make suggestions.

The Barlow Commission mainly scrutinised the growth of industry and population during the interwar period that had been exceptionally concentrated in the flourishing areas like Midlands, Lancashire, Yorkshire or London. This led the Commission to investigate urban issues such as public health, housing, traffic congestion, patterns of journeys to work, land values and even imminent threats such as dangers from enemy bombing attacks on big cities. Summarily, through their quantitative comparisons between the advantages and disadvantages of life in large cities gave the conclusion that the disadvantages far outweighed any advantages, the Commission approved the general idea of creating new towns together with controls on the growth of conurbations.

The aftermath of the Barlow report, which submitted to the British government in February 1940, was a succession of new committee work and report writing, from 1941-1947. Similar kinds of report, acknowledged commonly after their chairman - Scott, Uthwatt, Abercrombie, Reith, Dower, Hobhouse - laid the foundations for the post-war urban and regional planning system in Britain. As recommendations on several specialised areas of planning were proposed to the government, many laws were legislated based on the essence of their recommendations which turned on the notion of widespread decentralisation of population and employment. The post-war planning system was formed by a series of Acts including: the Distribution of Industry Act 1945, the New Towns Act 1946, the Town and Country Planning Act 1947, the National Parks and Access to the Countryside Act 1949, and the Town Development Act 1952 (Hall 2002). Since the end of the Second World War, the implementation of these decentralisation policies formulated by the British government has been embraced world wide for example in Australia, Brazil, Canada, Finland, France, Germany, India, Israel, Italy, Japan, Netherlands, South Africa, Sweden, the United States (Osborn & Whittick 1963). Generally, the Barlow report created a chain reaction in the history of urban and regional planning, sparked off in Britain, leading up to the creation of the comprehensive and complex post-war planning machine during the years 1945-1952 (Hall 2002; Osborn & Whittick 1963).

The spatial structure of the city has completely shifted from high density and mixed-use development with walking distance dominating its structure into a decentralised style which is widely known now as 'urban sprawl'. The main factors and events that interact with each other and finally led to the emergence of decentralised style of the city development, which we elaborated from Sections 2.1.1 to 2.1.4, are summarised in Figure 2.3.

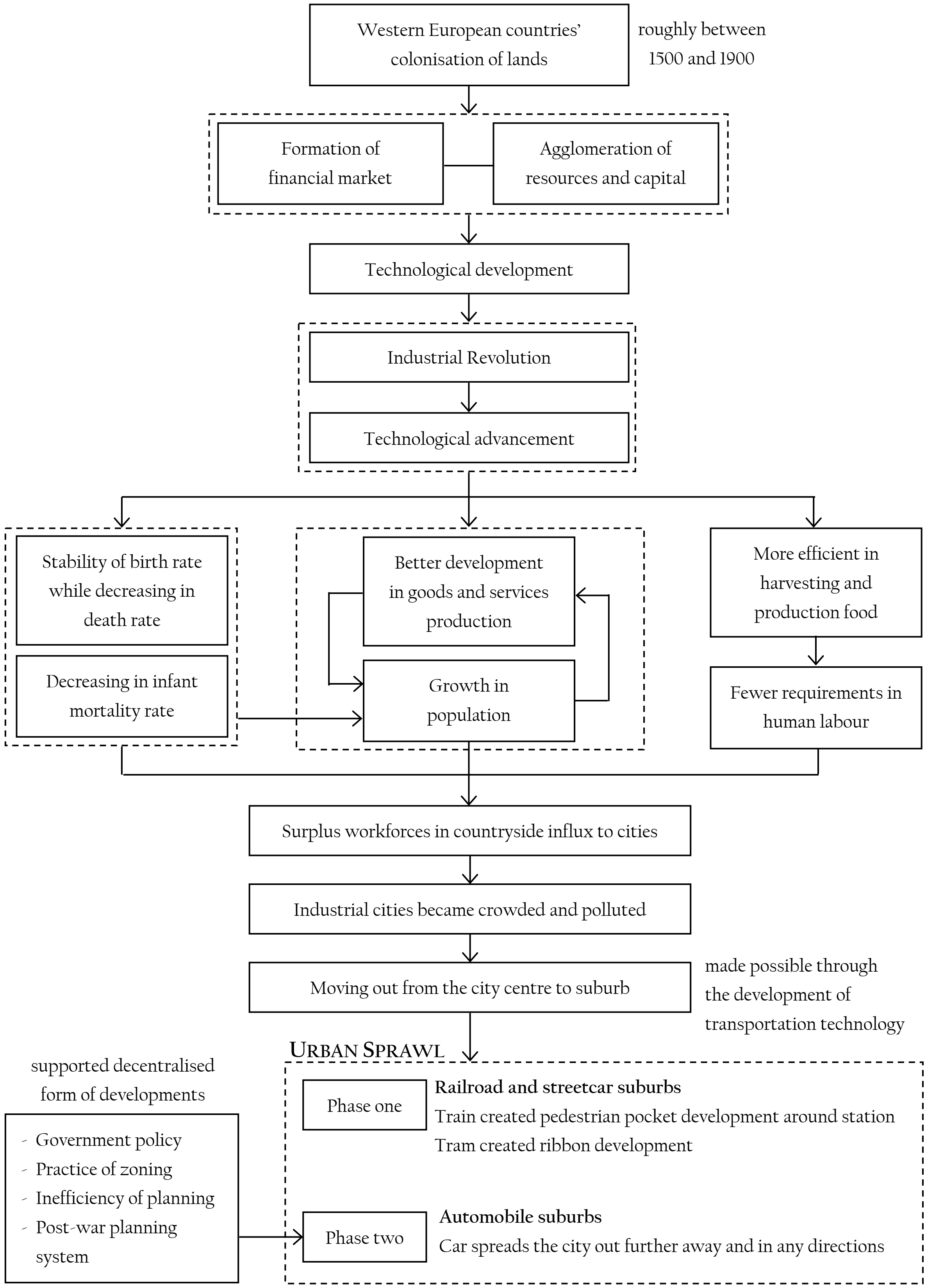


Figure 2.3: Conceptual flowchart exhibiting the connection among various factors and important events leading to the emergence of urban sprawl

2.2 The Origin of the Term Sprawl

On 7 November 1883, William Morris, an English architect, furniture and textile designer, artist, writer, and socialist, gave a lecture at University College Hall, Oxford. He commented on the emergent suburbs of London as follow:

> Not only are London and our other great commercial cities mere masses of sordidness, filth, and squalor, embroidered with patches of pompous and vulgar hideousness, no less revolting to the eye and the mind when one knows what it means: not only have whole counties of England, and the heavens that hang over them, disappeared beneath a crust of unutterable grime, but the disease, which, to a visitor coming from the times of art, reason, and order, would seem to be a love of dirt and ugliness for its own sake, spreads all over the country, and every little market-town seizes the opportunity to imitate, as far as it can, the majesty of the hell of London and Manchester. Need I speak to you of the wretched suburbs that 'sprawl' all round our fairest and most ancient cities?

In a working paper entitled 'The Connection between Local Government Finance and the Generation of Urban Sprawl in California', Robert W. Wassmer credited to Thomas Black the initial modern usage of the terminology sprawl. The term was employed for the first time in Earle Draper's speech to the national conference of planners in 1937 where he said:

> Perhaps diffusion is too kind of word … In bursting its bounds, the city actually 'sprawled' and made the countryside ugly … uneconomic [in terms] of services and doubtful social value.

In the preface to *Garden Cities of To-Morrow* by Ebenezer Howard, Frederic J. Osborn who authored the preface in 1946 launched the debate over sprawl development and its association with transportation and income:

> These new forms of transport ... were used ... to facilitate the 'sprawling of suburbs', a type of urban growth wasteful from the economic standpoint and disadvantageous socially. Coupled with the rise of real incomes, rapid transport has enabled the people moving out from the centres to find the open residential surroundings they desired. But they and the numerous immigrants from rural areas have obtained these surroundings at the expense of long and costly daily journeys to and from work. Local community life has been weakened or destroyed, and access to the country made more difficult for the large numbers of residents still left in the city centres.

While the first anti-sprawl action in London appeared in *The Restriction of Ribbon Development Act 1935*, not until the late 1950s in United States with post-war suburban development becoming a major problem, a young journalist and a member of *Fortune* magazine called William H. Whyte convened what was possibly the first conference about sprawl. Selective essays were collected after the conference by Whyte and published in a book entitled *The Exploding Metropolis*. In his own introduction and essay called *Urban Sprawl*, he brought the term to wider public recognition (Bruegmann 2005).

It was in the 1960s that the US Council on Environmental Quality, the Department of Housing and Urban Development, and the Environmental Protection Agency financially sponsored the Real Estate Research Corporation, a private organisation researching and working with real estate in Chicago, to accomplish the earliest influential literature review of sprawl while also serving as the first originator of America's first anti-sprawl campaign. The report studied 10,000 residential units in each of 6 communities ranging from high to low levels of density but with considerable planning. The focal point of this literature led to a three-volume monograph *Costs of Sprawl* issued in 1974. Furthermore, this report contributed two major impacts on the issue of sprawl which are still significant to the present day. First, through its collection of the latest literature and statistical test sections, the essence of the report made a stand that favours compact settlement in a more empirical way than other preceding commentaries and research had done before. Second, the report allowed the authors to summarise the fact that unplanned growth was more expensive than planned developments of a more compact nature (Real Estate Research Corporation 1974). In other words, compact development was highly praised in this report which in turn also implied that the blame for low-density development was predominantly due to urban sprawl.

Numerous critiques were made about this conclusion in terms of a lack of concern for the size of houses and apartments and how this relates to how the statistical model fits the real situation. Moreover, it was not logically proven that low-density areas are intrinsically more costly due to the primary explanation that units in more packed settlements are usually smaller in size than ones in low-density settlements. Moreover, the additional view that such dispersed cities could dynamically become proficient higher-density development by urban infill development was not really explored. Furthermore, the report itself posed one debatable but classically crucial problem in most social science research that copes with complex phenomena. This is about getting complete data, controversy in its research assumptions, and thus the identification of the key research factors. Consequently, the outcomes and conclusions are unavoidably based on the subjective intuitions of the researcher's viewpoint. Nevertheless, the summary made from this study has supplied the classic ground for various descendants in terms of research and data used for legitimation by anti-sprawl groups (Real Estate Research Corporation 1974).

Around the same time, a milestone work observing Levittown, a new suburb town in Willingboro, New Jersey, United States was produced by Herbert J. Gans. Levittown started its construction around the mid-1950s by Levitt and Sons, Inc. and was formally opened to purchasers in 1958. It was a post-war suburbia archetype consisting of 10 neighbourhoods with approximately 1,200 houses within each neighbourhood. Through the participant-observation technique as the main method in collecting data during October 1958 and September 1960, Gans' (1967) book *The Levittowners: Ways of Life* *and Politics in a New Suburban Community* demonstrated the benefits of suburban life in terms of family solidity and significant heightening in community spirit throughout the lessening of monotony and solitude. Several random samples were discussed on attitudes toward suburbs and cities in two interviews; the majority liked living in Levittown very much, none disliked it, and only some had a conflict of opposing attitudes. Moreover, no one from the interviewees planned to return to the inner city (Gans 1967), even though the prevailing theme among scholars continued (even to this day) to be against urban sprawl.

2.3 Causes and Consequences of Urban Sprawl

It is widely suspected that sprawl phenomena more or less hold to specific features but vary in different changing contexts. Most literature about urban sprawl has scrutinised cities in United States and is developed by North American academics while relatively little research exists on the phenomena in Europe or on other continents (Couch et al. 2007; Phelps et al. 2006). Consequently, it can be said that, in such field, the United States is the pathfinder in the study of sprawl and academics and commentators have discussed the issue much more intensively than those in other countries. Furthermore, sprawl in Europe and North America does share some attributes and characteristics (Couch et al. 2007), and therefore it is reasonable to investigate sprawl from the US urban sprawl research experience and literature. Yet although the main objective of this research is not in the pursuit of what causes sprawl, it is still important to identify the differences in the causes of sprawl between both parts of the world so that we might grasp the limitations of this various research.

Couch, Leontidou, and Petschel-Held (2007) propose four main contextual differences that distinguish urban sprawl and its control between the United States and Europe (Table 2.1). This provides a broad view of the American context and contains elements that tend to focus more on sprawling patterns of urban form than their European counterparts.

Table 2.1: The comparison of four main contextual differences of European countries to the United States (adjusted from Couch et al. 2007)

Contextual differences	The comparison of European countries to the United States
Policy and governance	More favoured in the concept of domination and superiority of the market and market-led approaches
Local government structure	Relatively less units of local governments
	Higher dependency of local authorities on higher levels of government particularly in terms of funding
	More control over local authorities by central and regional governments with reference to development direction
	Local governments are less independent; however, more solid in their structures
Political and scientific concern for sustainable development	More energetic in environmental policy
	More reliability in tackling urban development and problems in terms of sustainable development within country and among European Union countries
Economic geography and scale of urban problems	More sense of land scarcity (e.g., urban area in UK occupies about 7.5% of the total land area while it is 1% in the US)

Furthermore, for an academic exploration of the causes of urban sprawl, there are some comparative issues in terms of context which are worth paying attention to. These are: 1) the variation in planning theories and systems behind the scene, 2) public and private transportation usage behaviour (Nechyba & Walsh 2004), 3) public investments in central facilities and road infrastructure, 4) culture in household mobility, 5) racial tension and racial segregation or heterogeneity within cities, and 6) scale, growth rate, living conditions between sprawling suburbs and downtowns (Couch et al. 2007; Nechyba & Walsh 2004), and developments in technology.

In a very broad sense, Wassmer (2001) proposed that sprawl is a synonym for over-metropolitan decentralisation or excessive suburbanisation. In other words, sprawl is something more than simply suburbanisation (Brueckner 2000). This synonym of sprawl raises two further fundamental questions. The first question focuses on what suburbanisation is. Suburbanisation, in general, is a term used to describe the process of population movement from within cities to the rural-urban fringe due to the fact that the metropolitan area's residential and business activities occur outside of its central locations. The dispersion process in urban areas, particularly in the case of US cities, results largely from the following key issues: rising incomes, decreasing travel costs, growing population (Brueckner 2000; Wassmer 2001), technological change and innovation (Ewing 1997; Gordon & Richardson 1997), the shifting of consumer tastes in location preferences (Ewing 1997; Wassmer 2001), government taxes, local fiscal expenditures (Mieszkowski & Mills 1993), and State and Federal zoning policies (Downs 1999; Ewing 1997; Wassmer 2001).

Another question relates to how and when decentralisation turns out to be excessive. The concept of microeconomic constrained optimisation helps clarifying how one makes a decision whether to live far away from the city centre or not by looking at the trade-off between private benefits and private costs (Wassmer 2001). For instance, it is the choice between cheaper land with a larger house and longer distance to the central city or higher costs of transportation to the central business district and vice versa. Furthermore, residential preferences for local amenities explicate residential location choices with cooperation between push and pull forces (Tiebout 1956). Inner city problems like higher crime rates help push city dwellers to leave central cities. The pull force mostly revolves around advantages from agglomeration of peer mobile households such as exclusion from those who are expected to create negative externalities for instance low quality of schooling or free-riders on tax payments (Nechyba & Walsh 2004).

Each decision maker involving household or business location directly and indirectly generates social costs such as higher congestion with greater air pollution. This is the boundary where sprawl begins, in an economic sense, when total private costs are greater than social costs (Wassmer 2001) which we show in Figure 2.4. In this sense, sprawl results from a myriad of individual choices and the comparison of the population's utility levels and these are often theoretically impractical; therefore, these causes of sprawl only assist in a broad picture of sprawl but not a proper piloting to identify sprawl indices. Furthermore, apart from consumer preferences for residential location, other reasons are raised as key factors generating sprawl including technological innovation and uncoordinated planning.

Burchell, et al. (1998) hypothesised that the costs of sprawl are mostly converted to individuals while creating impacts at a publicly larger scale. For instance, groups of residents or businesses select locations in low density areas and gain benefits in terms of obtaining more safety, open space, convenience in commuting, and better facilities and amenities but this effect can clearly viewed at a different level, at an international level in terms of the decrease in agricultural production. Various researches have discussed the costs of sprawl (Brueckner 2000; Bruegmann 2005; Ewing 1997; Ewing et al. 2002; Galster et al. 2001; Gordon & Richardson 1997; Longley et al. 2002; Nechyba & Walsh 2004; Real Estate Research Corporation 1974; Transportation Research Board 1998; Wassmer 2001) based on socioeconomic and environmental aspects ranging from congestion, pollution, energy consumption, loss of open space, and so on. Nevertheless, in real-world situations, the above impacts are not caused purely by sprawl. In other words, one negative outcome derives from a combination of various sources and sprawl can be one of its ingredients. Furthermore interrelationships among elements also exist within such ingredients. Taking air pollution as an example, the industrial sector could be the vital actor responsible for a major share in polluting the air rather than urban sprawl per se. In fact, sprawl harms the atmosphere to a certain degree even though, by this argument, treating sprawl as the first priority in solving the air pollution problem would not make sense. It is wider than this and thus we must be very careful in identifying causes of sprawl and even more careful in proposing remedies, if remedies are to be sought.

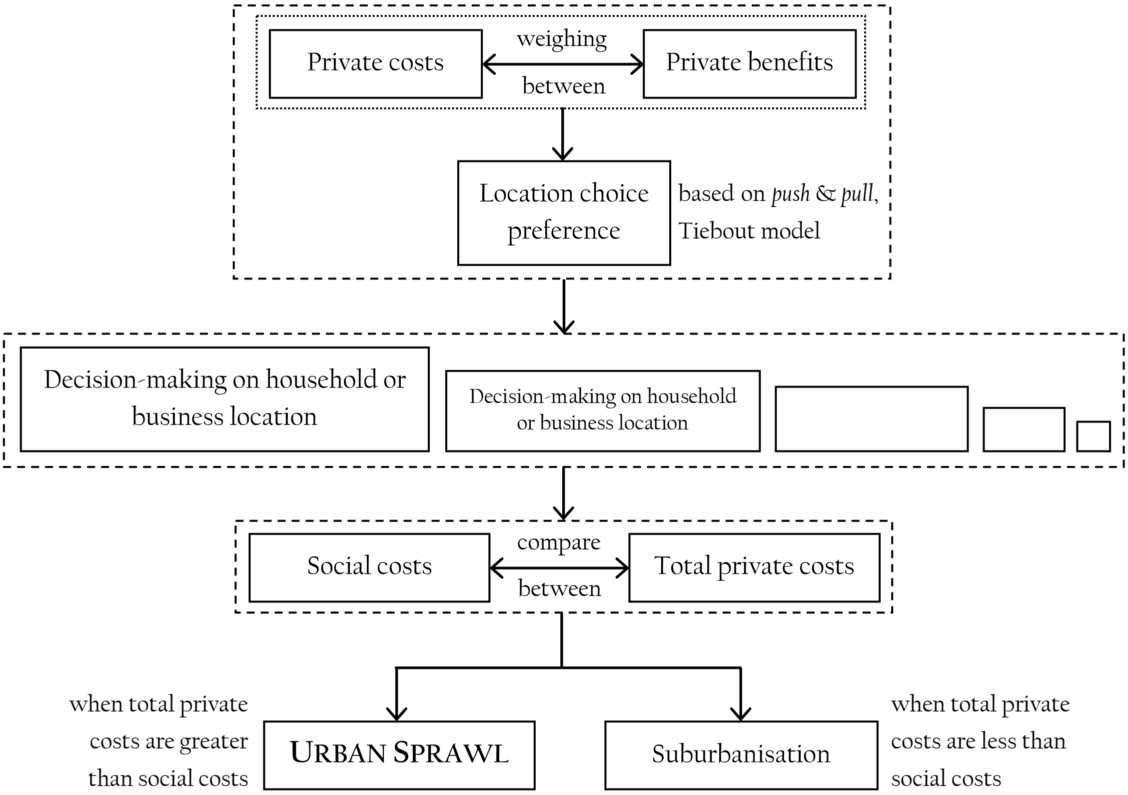


Figure 2.4: Causes of sprawl from a microscopic constrained optimisation viewpoint

In a more detailed example, in a high air-polluted area with a situation of people moving away from the city centre while their workplaces are still located in the core, many more elements are still needed to investigate this phenomenon. As is widely known, Vehicle Miles of Travel (VMT) determines the level of fuel consumption and carbon dioxide emissions (Ewing 1997). In this case, the average VMT of the city is supposed to increase but under a successful policy of decentralisation of jobs, air pollution may derive from other sources such as industries. Or in the case where the average VMT may still be high, limitations in public transportation infrastructure or people's behaviour in commuting might be able to explain the phenomenon. Other elements in a given context are always necessary to take into account.

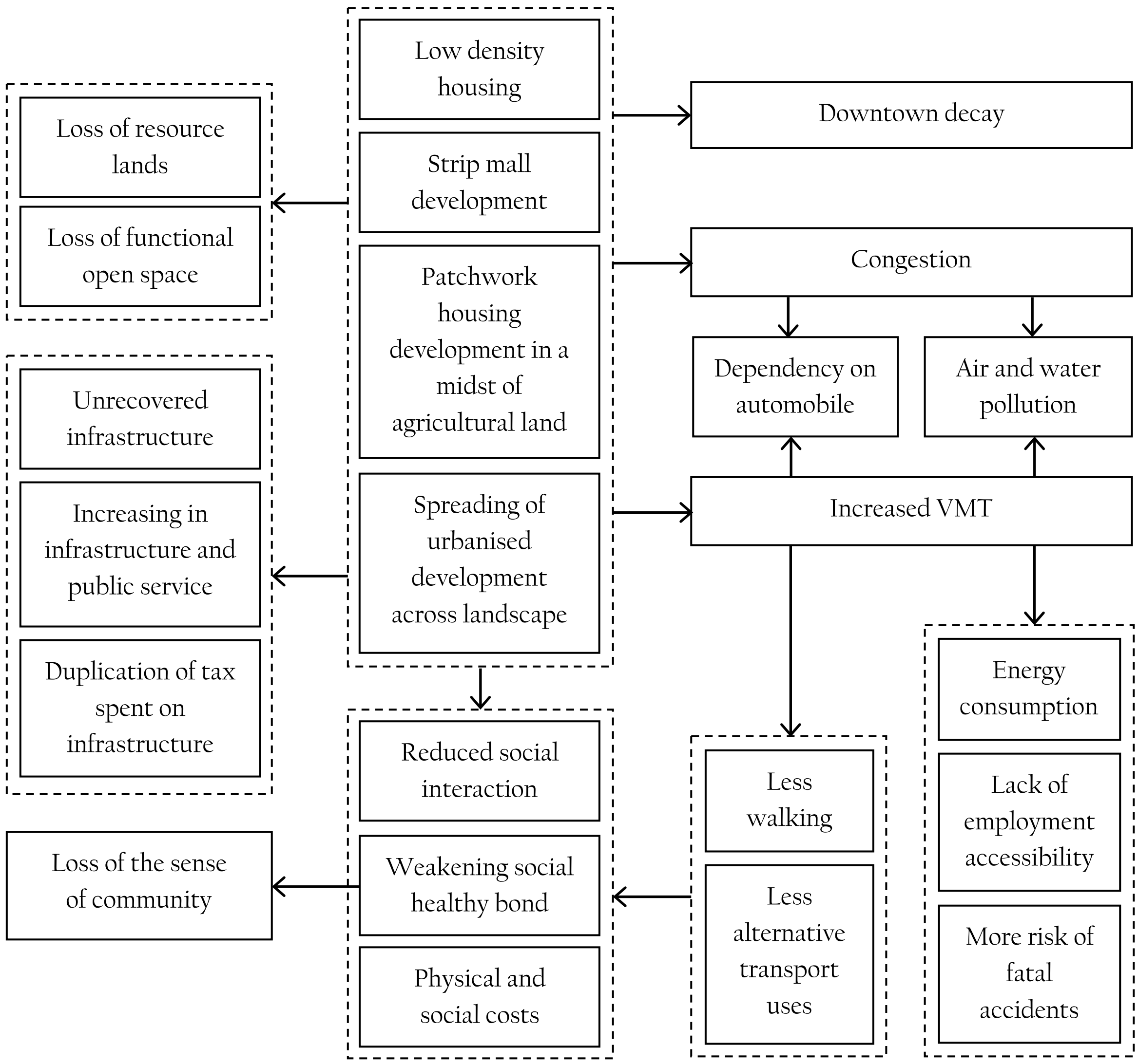


Figure 2.5: Relationships between the negative consequences of sprawl

Urban sprawl is a multidimensional issue with multiple causes and effects (Frenkel & Ashkenazi 2008; Nechyba & Walsh 2004). Furthermore, both negative and positive consequences of sprawl also vary according to context and to the researcher's point of view. The positive side of sprawl is often neglected while its negative consequences are abundantly clear in many literatures. It is worth summarising these impacts in a flowchart which we do in Figure 2.5, displaying the relationships among them.

2.4 Definitions of Urban Sprawl

Several investigations into the definition of sprawl and its attributes have been conveyed in order to serve many objectives including pursuit of the ways to measure sprawl. Since the first anti-sprawl movement in 1930s in Britain and in 1950s in US, until now there have been diverse approaches to viewing and defining sprawl among scholars. At the core of these various influential definitions, Ewing (1997) has proposed that

> sprawl is the spread-out, skipped over development that characterizes the non-central city metropolitan areas and non-metropolitan areas of the United States.

The Sierra Club (1998) has defined sprawl as

> low-density development beyond the edge of service and employment, which separates where people live from where they shop, work, recreate, and educate, thus requiring cars to move between zones.

According to the sprawl definition defined by Transportation Research Board (1998) in terms of the form of urban development, sprawl is characterized by the following ten elements:

1) Low residential density,
2) Unlimited outward extension of new development,
3) Spatial segregation of different types of land uses through zoning regulations,
4) Leapfrog development,
5) No centralized ownership of land or planning of development,
6) All transportation dominated by privately owned motor vehicles,

7) Fragmentation of governance authority over land uses between many local governments,

8) Great variances in the fiscal capacity of local governments because the revenue-raising capabilities of each are strongly tied to the property values and economic activities occurring within their own borders,

9) Widespread commercial strip development along major roadways, and

10) Major reliance upon the filtering or "trickle-down" process to provide housing for low-income households.

Galster et al. (2001) has recommended that sprawl

> has been attached to patterns of residential and nonresidential land use, to the process of extending the reach of urbanized areas (UAs), to the causes of particular practices of land use, and to the consequences of those practices.

Peiser (2001) explained the definition of sprawl as

> the term is used variously to mean the gluttonous use of land, uninterrupted monotonous development and inefficient use of land.

Urban growth happens when the amount of urban in-migration is more than emigration or when the birth rate surpasses the death rate. In other words, the size of the urban population defines urban growth (Clark 2003). As a result, increases in population generate spatial requirements generally for residential uses which also cause an expansion in the land area of the city. The crucial point lies in how the city grows and the form that this takes and this relates to density and of course the degree of compactness or sprawl. Oktay and Conteh (2007) proposed that unplanned, incoherent and scattered growth is called sprawl. They further defined it as

> sprawl is the process in which the spread of development across the region far outpaces population growth with four dimensions: 1) a population that is widely

dispersed in low-density development, 2) clearly separated homes, shops, and workplaces, 3) a network of roads marked by very large blocks and poor access, and 4) lack of well-defined activity centres, such as town centres.

The word *sprawl* has been used by many disciplines and subject areas, applied in different contexts, and exhibited in various ways. In other words, the term was invented without harmonious definition and as a result, there is no universal agreement in causes, characteristics, outcomes, and methods in measuring the phenomenon. However, the definition of sprawl can be presented mainly in terms of eight categories and these will be discussed in the next section.

2.4.1 Definition of Sprawl Based on Form and its Archetypes

According to the form-based definition, sprawl is a matter of degree (Ewing 1997), not any particular set of forms per se (Longley et al. 2002; Longley et al. 2002), thus ranging from compact to completely scattered development (Ewing 1994; Peiser 2001; Pendall 1999) . It also provides as an antonym for compactness (Ewing 1994).

Harvey and Clark (1965) introduced three forms of sprawl: low-density continuous growth, strip development, and leapfrog development. Low-density continuous development stands at the lesser sprawl end of the continuum while scattered or leapfrog development sits at the other end of this scale. It is important to remember that a lesser degree of urban sprawl in the form of low-density and continuous development called suburban development or the continuous extension of existing area from a city centre (Hall 1997) is not actually characterised as sprawl in some studies (Batty et al. 2002).

The difficulty lies in the ambiguous line between differentiating real world developments such as *commercial strips* versus *activity corridors* or *leapfrog development* versus *discontinuous development*. Discontinuous development is a settlement pattern in which specific sites are sidestepped at the outset of the development in order to leave room for more intense uses later on, and activity corridors represent opportunities for strip growth along transportation paths (Ewing 1997). The former cannot be considered as sprawl if the bypassed land is designed to be filled with more intense uses (Peiser 1989) while the latter cannot also be called sprawl if those corridors contain the density and the mix of land uses designed to provide backup transportation options to the automobile (Lessinger 1962). Moreover, the form of leapfrog and scattered development display broken growth, spreading into unoccupied land away from older city centres. According to Ewing (1994), scattered development often assumes a monocentric form, whereas leapfrog development appears as a more polycentric style of development.

Another case lies between compact growth around a number of sub-centres and the poly-nucleated city where its downtown is served by more distant centres. The poly-nucleated type of urban from is classified as sprawl while the other one is not. The difference between these two types of development relies on the level of services proposed by its centres and the level of interaction between centres and surrounding suburbs. From the aforementioned developments, it is a main challenge in practice to distinguish between those types of development and sprawl.

2.4.2 Definition of Sprawl Based on Density

Density is expressed as the proportion of the number of residential units or population size to area units. It is a quantitative term; however, it has neutral properties because a given density does not imply either a positive or negative meaning. Across a broad-spectrum, measuring density depends on its numerators and denominators whereas some delineate density through population which is an activity while others use residential density which relates more to land use. The difference between the two is that population density uses numbers of people as its numerator while residential density uses numbers of dwelling units (Churchman 1999).

Many definitions of sprawl are based on the idea of density (Batty et al. 2002; Ewing 1997; Fulton et al. 2001; Ottensmann 1977; Peiser 1989) and these reflect low density, decreasing density, and functional disintegration of a city into implicit urban sprawl. Nevertheless, the concept is neither clearly explained nor well quantified. Moreover, concepts and perceptions of density are relative and change according to regions and cultural anticipations (Batty et al. 2002).

Parcel density is based on measurement assigned to residences and it can be presented in two ways: as dwelling units per area and floor area per area. The denominator used in this type of density measurement is specifically designated and that is why Churchman (1999) suggested four types of density measures for residential areas: 1) parcel density, 2) street density, 3) gross residential area density and 4) density that measures areas beyond residential density per se. Parcel density may be the clearest measurement among these density measurements. The proportion between floor area and lot area is presented in the measurement of floor area per area density. Roads, parks and other public space are excluded while calculating only parcels associated with residences in its denominator defines the density of dwelling residential units per area. But in some cases, net density includes neighbourhood-related spaces in its computation (van Andel 1998). There is no agreement about these measures and this makes comparison between different studies and different the contributions of different authors extremely difficult.

Then main point is that attention should be carefully paid to defining the denominator in both cases of net density and gross density. Taking account of reserved and un-developable land then this may undervalue density as such land has no potential for any development, while omitting some potential land for development in density estimation, may lead to problems of overestimation. Batty et al. (2002) suggested that neglecting reasonable un-developable land in describing density may make more sense for in practice; it is hard to avoid the issue of subjectivity in determining what is un-developable land in every single case.

2.4.3 Definition of Sprawl Based on Land-use Patterns

Sprawl is also expressed in terms of land use patterns. Harvey and Clark (1965) described these types as contiguous low density development at the rim of a metropolitan area, as constituted by leapfrog development over undeveloped land and as ribbons of low density development along major transportation routes.

Spatial seclusion of single land uses is at the heart of defining sprawl via the land use approach. The spreading out of single functional use includes principally low density residential development, freestanding shopping malls, and non-residential uses incorporating industrial or office parks (Transportation Research Board 1998). This land-use based definition is often defined together with form-based one (Batty et al. 2002) and we will elaborate all these ideas in the following sections.

2.4.4 Definition of Sprawl Based on Urban Processes

Along with Couch et al.'s (2007) perspective on sprawl, explaining sprawl as a process of urban change, may be a more useful viewpoint particularly due to the fact that in the process of sprawl, development policy must always take account of. Galster et al. (2001) recommended that

> sprawl is a pattern of land use in an urbanised area that exhibits low levels of some combination of eight distinct dimensions.

Couch et al. (2007) also view the conceptual and operational variables developed from these eight dimensions: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses and proximity, and argue that these could be regarded as a process rather than simply a pattern of urbanisation. Even though Galster et al. (2001) did not develop these in terms of process, they continued their work by assessing those variables in 13 large cities in the United States and argued that measuring sprawl patterns at distinct periods of time would be capable of unveiling the process itself. This definition-based view of sprawl has the potential to bring out the quantitative quality of the patterns of urban sprawl. However, high demands on data are the classical difficulty, obstructing this approach from pervasive applications. Moreover the inconsistencies in the nature and availability of data among different contexts are not a trivial factor that can be overlooked.

2.4.5 Definition of Sprawl Based on Impacts

According to Batty, Chin et al. (2002), Ewing (1994) was the first researcher who developed a definition of sprawl based on impact and this was followed by Johnson (2001) and Razin & Rosentraub (2000). They defined sprawl by its costs in terms of the lack of functional open space and poor accessibility among related land uses. Other negative externalities of sprawl are reflected in traffic induced in the form of increased vehicle miles traveled, high energy consumption, air pollution, loss of potential resource land, increases in infrastructure and public service costs, harm to the prosperity of central cities and downtowns, and the imposition of psychic and social costs (Downs 1999; Ewing 1997).

Not only does this approach deal with sprawl indirectly but it also attempts to brand any developments with negative impacts as sprawl and this may lead to problems of prejudgment (Batty et al. 2002).

2.4.6 Other Approaches to Defining Sprawl

There are three more approaches to defining urban sprawl. First, sprawl is defined as the outcome or consequence of an independent variable, for example as the result of land policy and regulation (Black 1996; Transportation Research Board 1998). In this approach, urban sprawl is viewed as a dependent variable. Second, sprawl is, on many occasions, believed and considered to be ugly and monotonous due to its homogeneous form of growth (Fulton 1996; Gordon & Richardson 1997). Through this intrinsic subjectivity, it is quite tricky to evaluate the aesthetics of sprawl (Frenkel & Ashkenazi 2008). Torrens & Alberti (2000) suggested that more work is required in understanding more about the ugliness of sprawl. The last approach reviewed above is a definition of sprawl based on the archetypical example of Los Angeles which always wins out in this debate. Moreover, the example-based definition of sprawl is usually the one critiqued in relation to the visual aesthetic (Couch et al. 2007).

From the reviewed definitions of sprawl discussed in Sections 2.4.1 to 2.4.5, we have made some attempt to cover every aspect of sprawl; however, these leave much for interpretation and do not tend to be very precise or focused. Therefore any urban development could be labeled as sprawl development when this wide range of definition is applied. Alternatively, the other reviewed definitions of sprawl are too specific, so there is no single type of urban development that can completely fit the term. In other words, if the definition is not too broad, it is too detailed and both concepts become almost ineffective, cancelling one another out. This is a classical problem when attempting to wrestle with conceptual terminology like sprawl

The word *urban sprawl* has been used by many disciplines, applied in many different contexts, and exhibited in various manners. However, there is no clear line agreed for differentiating among these different terminologies like dispersed development, scattered development, decentralised development, low-density development, suburban development, leapfrog development, and so on. We have shown that sprawl is an ambiguous term that can be viewed and interpreted in many different ways. In other words, as we have said, the term was 'ideologically' invented with no attempt at any harmonious definition and as a result, there is no universal agreement on causes, characteristics, outcomes and methods for measuring it. However, as a conclusion to these reviewed definitions of the characteristics of urban sprawl, we consider that this thesis has already benefitted by making the term clearer, also pointing to the advantages in generating a 'sprawl index' which will be one of the main outcomes of this thesis.

2.5 CRITERIA FOR FILTERING CHARACTERISTICS OF SPRAWL

The conceptual and operational characteristics of sprawl can be sieved from the reviewed definitions in order to make one further step in this study which will measure levels of sprawl. These conceptual characteristics of sprawl will be developed into operational variables in the following chapters, which is consistent with the objectives of this study which are to develop such indicators in a quantitative and measurable way.

At this stage the study requires a set of criteria in filtering the reviewed definitions in order to form a set of unique characteristics of urban sprawl. In developing the sprawl index, this study will adopt some of the criteria proposed by Lopez and Hynes (2003) in defining sprawl and Coulter (1989) in forming indexes of inequality. These criteria include: 1) objectivity, 2) interpretability, 3) applicability and 4) simplicity.

The first and second criteria, *objectivity* and *interpretability*, work harmoniously with the proposition stating that sprawl is a matter of degree, and thus establishing that it can be measured. Both criteria are applied to set out a working definition and set of characteristics defining sprawl at this stage. Moreover, quantitative aspects of sprawl are *applicable* to all cities or metropolitan areas. So the first step is to eliminate definitions that rely on subjective aspects and continue developing objective ones.

Not only will these aforementioned criteria be applied in sieving out the key characteristics of sprawl, these aforementioned criteria will be discussed again in the section where we will identify the most suitable indicators for each operational dimension of sprawl which we will return to in Chapter 6.2.

2.6 CHARACTERISITCS OF URBAN SPRAWL

At the heart of these criteria is the condition of *objectivity*. This can be applied to set out a working definition and characteristics of sprawl at this stage. Thus, the first step is to eliminate the definition that contains subjective aspects and continue developing the objective ones into operational variables which meet other criteria.

Operational variables that are developed from subjective-based definition tend to rely on subjective measurements which are hard to quantify. In the case of form-based definitions, this describes urban sprawl as three kinds of development: 1) continuous low-density residential development, 2) ribbon low density development along major suburban highways and 3) leapfrogging of new development past already developed land into a patchwork of developed and undeveloped tracts. In practice, these are too vague and too risky to assess a development as being linear or leapfrog. Furthermore, this definition also involves the issue of the scale of observation. Consequently, previous operational measurements are kept out even if the study takes elements of a form-based definition into account. Instead, examining and clarifying the spatial pattern of development after calculating their degree of sprawl may provide inferences back to the form-based definition of urban sprawl. In short, we prefer to measure sprawl at first as unambiguously as we can and then consider more subjective definitions based on form after we have generated these more objective measures

It can be said that every single consequence that appears in the form of urban phenomenon is the result of interplay of various factors. Taking the impact-based definition into account for developing the sprawl index means that this study will deal with the physical phenomena of sprawl indirectly. Furthermore, in doing so tends to label any development with negative impacts as urban sprawl and also leads to lead to the issue of prejudgement (Batty et al. 2002). The dependent-variable-based definition falls into this argument as well. Focusing on what causes sprawl does not provide much sense in quantifying sprawl.

In the case of defining urban sprawl through evaluating aesthetic factors, this could be another research direction based on the subjective approach which varies according to people's experiences and perceptions (Frenkel & Ashkenazi 2008). Centring the study on a perceived-aesthetic perspective brings about many problematic questions e.g., what happens when people's preferences change? Furthermore, a better-looking city may derive from policy goals pertaining to aesthetics. Approaching sprawl through aesthetic qualities leads a wide range of expressions and comments, although the subjective nature of it leaves little room for quantification (Lopez & Hynes 2003; Torrens & Alberti 2000). This is why such an index based on such personal opinions is not useful in this study. Moreover, cases of example-based definitions of sprawl often rely on a particular person or group's opinion which is purely based on a subjective approach.

It is reasonable to consider the past and present states of cities in order to understand and forecast their future; however, with regard to an urban process-based definition, a series of maps and census data will be involved. We have decided not to take this process-based definition into account due to limitations in data availability but we will make this clear in later chapters. Furthermore, as this study is interested in urban sprawl as signifying a condition that characterises a city, we will not deal with the process of development per se.

In summary, definitions of urban sprawl based on form, impacts, dependent variables, aesthetics, and examples will not be taken into consideration further due to the main reason that these conceptual variables embed subjective rather than objective qualities into the characterisation of sprawl. This does not however mean that these other approaches have no value, far from it, but that here measurement is the key criterion for definition and identification of what constitutes sprawl. Consequently, at this point the study takes density- and land-use pattern-based definitions of urban sprawl into consideration. Major quantifiable variables and characteristics of urban sprawl will then be extracted and synthesised into operational variables as implied in Table 2.2.

Table 2.2: Summary of the definition-based and main characteristics of urban sprawl

Definition-based urban sprawl	Main characteristics of urban sprawl
1) Density	1.1) Low density
2) Land-use patterns	2.1) Spatial seclusion
	2.2) Single functional usage

At this point, it can be seen that the three quantifiable characteristics of sprawl we have obtained and which are shown in Table 2.2 rather support the multidimensional aspects of sprawl mentioned in the second proposition of this study (Section 1.3). Notwithstanding this conclusion, further investigations are still required. Searching for appropriate techniques and tools to measure the two main conceptual variables in Table 2.2 is the next essential task. Prior to that, previous attempts at measuring sprawl and relating conceptual and operational dimensions of sprawl are worth paying attention to and these will be reviewed in Chapter 3.

CHAPTER 3: DIMENSIONS OF SPRAWL

The specification of conceptual characteristics of sprawl – low density, spatial seclusion, and single functional usage that we introduced at the end of Chapter 2, facilitates this study in generating operational dimensions of sprawl which can be objectively measured. In this section, previous studies that have attempted to measure sprawl will be examined since, through a series of quantitative variables, they facilitate revealing major applications to measuring sprawl while also in setting up the conceptual and operational dimensions of sprawl that are essential for any measurement of this phenomenon.

3.1 PREVIOUS ATTEMPTS AT MEASURING SPRAWL

Recent studies conceive sprawl as a multidimensional phenomenon for which a diverse set of indicators are needed with respect to each dimension of sprawl (Torrens & Alberti 2000; Galster et al. 2001; Ewing et al. 2002; Wolman et al. 2005; Frenkel & Ashkenazi 2008). Various sprawl measures proposed and tested in such literatures can be classified into five main approaches based on: 1) density, 2) socio-economic activities, 3) accessibility, 4) spatial geometry and 5) growth rates, to which different parameters can be applied that make these variables distinct to different applications.

First, density is the ratio between the objects of interest and the amount of area that these objects occupy. Different sets of measurable factors are used as numerators of density in determining sprawl and these include: population (Burton 2000; Ewing et al. 2002; Ewing & Rong 2008; Frenkel & Ashkenazi 2008; Galster et al. 2001; Garcia-Palomares 2010; Hasse & Lathrop 2003; Lopez & Hynes 2003; Malpezzi & Guo 2001; Razin & Rosentraub 2000; Silva et al. 2007; Tsai 2005), residential units (Razin & Rosentraub 2000; Wolman et al. 2005), number of households (Burton 2000), urbanised land (Hasse & Lathrop 2003), and numbers of employment or jobs (Garcia-Palomares 2010; Tsai 2005). Another type of density employed in measuring sprawl is the density gradient (Ewing et al. 2002; Malpezzi & Guo 2001). This measures how density declines when distance from a designated centre is increasing.

Second, in the socio-economic approach, the jobs-residents balance (Ewing et al. 2002) in terms of the number of jobs in the central city (Razin & Rosentraub 2000), the housing stock (Burton 2000), the percentage of workers according to age group, education and income, percentage of foreigners among new residents, percentage of foreigners out of the total population, level of motorisation, evolution of motorisation rates over a five year period which is sufficient to detect real change, and presence or absence of a commuter railway service and interurban bus coverage (Garcia-Palomares 2010), all these have been used in defining sprawl in quantitative terms.

Third, with the idea that sprawl is associated with stretched, giant physical blocks of uniform land use which are the outcomes of scatter, discontinuous and bending street layouts, in opposition to much more compact styles of development, Ewing et al. (2002) and Ewing & Rong (2008) have applied block lengths and block size to defining sprawl with respect to their approach to including accessibility.

Estimating sprawl through the notion of spatial geometry is perhaps the most significant approach used to estimate the degree of sprawl. Nine principal spatial geometric patterns can be implemented including: 1) complexity of shape (Frenkel & Ashkenazi 2008; Malpezzi & Guo 2001; Silva et al. 2007), 2) fragmentation or continuity (Frenkel & Ashkenazi 2008; Malpezzi & Guo 2001; Razin & Rosentraub 2000;), 3) clustering (Galster et al. 2001; Malpezzi & Guo 2001; Tsai 2005), 4) centrality (Ewing et al. 2002; Galster et al. 2001; Garcia-Palomares 2010; Wolman et al. 2005), 5) equality in distribution (Tsai 2005); 6) mix of uses (Ewing et al. 2002; Frenkel & Ashkenazi 2008; Galster et al. 2001), 7) concentration (Galster et al. 2001; Wolman et al. 2005), 8) nuclearity (Galster et al. 2001; Wolman et al. 2005) and 9) proximity (Galster et al. 2001; Wolman et al. 2005).

Finally, Burton (2000), Couch et al. (2007), Ewing & Rong (2008), Frenkel & Ashkenazi (2008), and Hasse & Lathrop (2003) have calculated sprawl in terms of growth or change rates. In the next section, operational dimensions of sprawl will be developed based on these reviews and then tested in terms of the conceptual dimensions and approaches that correspond to the characteristics of sprawl.

3.2 OPERATIONAL DIMENSIONS OF SPRAWL

Even non-physical aspects of the city tend to affect the way the city develops. However, as mentioned earlier in Section 1.3, according to the overall aim of this research, we have limited our focus only to urban physical form with respect to the measurement of sprawl. Consequently, socio-economic factors are largely omitted from this study. Similarly, the approach based on growth rates is left out of the study since the purpose of this study is to reveal sprawl at a cross section in time, which betrays the static point of view as mentioned earlier in Section 1.2. Furthermore, including street networks or road lengths overlaps with the dependent variable of this study which is the distance travelled, and in doing so, this tends to interfere and overestimate the relationship between the degree of sprawl sieved from its characteristics and the distance travelled made by private motorised modes in modelling sprawl. Other parameters i.e., loss of farmland, forest core habitats and natural wetlands, and increases in impervious surface areas are not included in this research as discussed in Section 2.4.5 for relating any of these negative impacts to sprawl implies a pessimistic prejudgement of sprawl, and this is something we wish to avoid

From the reviews of these conceptual characteristics of sprawl which involve low densities, spatial seclusion and single functional usage derived in Section 2.6, it is a fairly straightforward matter to include the density dimension for the purpose of its further development into operational variables. The reviews of tested operational variables with respect to the dimension of spatial geometry cover two other conceptual characteristics of sprawl which are spatial seclusion and single functional usage. Both features directly relate to the topic of urban physical form, and activities or land uses. Hence, this study adopts the disciplinary framework of landscape ecology, which has a long history of application to the spatial distribution of system components (Turner 1989). These include size, shape, amount, type, and arrangement of activities or land uses presented through a set of primitives for the built environment (Steadman et al. 2000), which in turn identify operational dimensions of sprawl through the approach based on spatial geometry. Our approach is thus manifestly physical as will become clear once we begin to construct the various indices of sprawl.

The discipline of landscape ecology underlies the investigation of spatial patterns and their degree of heterogeneity (Turner 1989). Two main facets are focused in terms of their geographical quantification: 1) Configuration which stresses the geometry or shape of urban premises, and 2) Composition which refers to the level of heterogeneity of activities or land uses (Boontore 2011a; Boontore 2011b; O'Neill et al. 1988; Torrens & Alberti 2000; Turner 1989). Such an approach spotlights the pattern of patches across the landscape, and through this perspective, we can define *polygons* of different land use types which we will refer to as *patches*.

In conclusion, the three key conceptual dimensions of urban sprawl that we use in the study are: 1) density, 2) configuration and 3) composition. They are listed in Table 3.1 along with the way we intend to turn these measures into operational dimensions of sprawl and potential indicators. It is important to state that for the group of research which takes the multiple dimensions point of view in measuring sprawl, there are gaps that this research is trying to bridge. As can be seen from Table 3.1, for most operational dimensions, there is naturally more than one indicator that can be used to estimate them. Using incomplete sets of indicators or subjectively applying an indicator to measure any operational dimension of sprawl could fail to represent sprawl quantitatively no matter what statistical techniques - factor analysis, principal component analysis, multiple regression analysis and so forth - are employed in deriving composite sprawl index (Burton 2002; Ewing & Rong 2008; Frenkel &

Ashkenazi 2008; Galster et al. 2001; Hasse & Lathrop 2003; Malpezzi & Guo 2001; Razin & Rosentraub 2000; Silva et al 2007; Tsai 2005; Wolman 2005). Furthermore, failure to examine correlation among indicators, or dimensions of sprawl, aggravates the situation since each indicator has a tendency for overlapping with others in the sense of measuring some common aspects of spatial distributions (Lopez & Hynes 2003).

Table 3.1: Summary of conceptual and operational dimensions of sprawl

Conceptual Dimensions of Sprawl	Operational Dimensions of Sprawl	Measurement	Potential Indicator
1) Density	1.1) Average density	The amount of affected components occupying a certain area	1.1.1) Average Land-use Density (ALD)
	1.2) Density gradient	How density decreases with distance away from the assigned centre	1.2.1) Density Gradient: Inverse power function (DGI) 1.2.2) Density Gradient: Negative exponential function (DGN)
2) Configuration	2.1) Complexity	Degree to which the city fills its two-dimensional space	2.1.1) Perimeter/Area Ratio (PAR) 2.12) Fractal Dimension: Slit-island method (FDS) 2.1.3) Fractal Dimension: Box method (FDB)
	2.2) Clustering	The extent to which components of interest are clustered or randomly distributed	2.2.1) Moran's I (MORAN) 2.2.2) Geary Coefficient (GC) 2.2.3) Index of Absolute Clustering (ACL) 2.2.4) Index of Spatial Proximity (ISP) 2.2.5) Index of Relative Clustering (RCL)
	2.3) Centralisation	Degree of closeness to assigned centre	2.3.1) Absolute Centralisation (ACE) 2.3.2) Relative Centralisation (RCE)

Table 3.1: Summary of conceptual and operational dimensions of sprawl (continued)

Conceptual Dimensions of Sprawl	Operational Dimensions of Sprawl	Measurement	Potential Indicator
3) Composition	3.1) Evenness	Differential distribution of groups of interests among areal units	3.1.1) Index of Dissimilarity (IOD) 3.1.2) Gini Coefficient (GINI) 3.1.3) Atkinson Index (AI) 3.1.4) Information Entropy Index (IEI) 3.1.5) Relative Entropy Index (REI)
	3.2) Concentration	Relative amount of physical space occupied by interested subjects	3.2.1) Delta (DEL) 3.2.2) Absolute Concentration Index (ACO) 3.2.3) Relative Concentration Index (RCO)
	3.3) Exposure	Degree of potential interaction between groups	3.3.1) Interaction Index (INT) 3.3.2) Eta squared index (ETA)

Additionally, prior to elaborating potential indicators of sprawl which we do in Chapter 4, and then using these indices to model sprawl in Chapter 6, it is important to re-emphasise that this research focuses sprawl on its residential aspects mainly through an analysis of residential land use. Three justifications support our stance encompassing: 1) residential activities as the main focus for living in the city, 2) the prominence in the amount of land area used and 3) residential activity in its role for defining the perception of sense of self and community. The main focus of the city is to provide residential space reflecting the amount of land use in any urban area. Besides, those who live in a city perceive and define their city fundamentally as a place in terms of residential location (Lopez & Hynes 2003). Even though other uses of land are also important, they are more or less subordinated to and influenced by the locations where people live. For instance, empirical findings clearly illustrate that employment sprawl follows housing sprawl by the presence of central-city dwellers who have moved to the urban fringe before their jobs departed from the inner city (Garreau 1992). In short, this thesis assumes for the most part that it is residential activity that is the main characteristic of urban sprawl; consequently, the residential aspect will be spotlighted in the structure of each potential sprawl indicator presented in Chapter 4.

CHAPTER 4: POTENTIAL SPRAWL INDICATORS

This chapter will elaborate indicators that can be used to estimate eight operational dimensions of sprawl as shown in Section 3.1: these are dealt with in the following sections as 4.1) average density, 4.2) density gradient, 4.3) complexity, 4.4) clustering, 4.5) centralisation, 4.6) evenness, 4.7) concentration and 4.8) exposure. We show these identifiers in Figure 4.1 in illustrative spatial form for two city tracts and these are used in most of the following equations. Definitions of variables and parameters are defined succinctly in that figure, and the reader needs to continually refer back to the definitions that are associated with this representation.

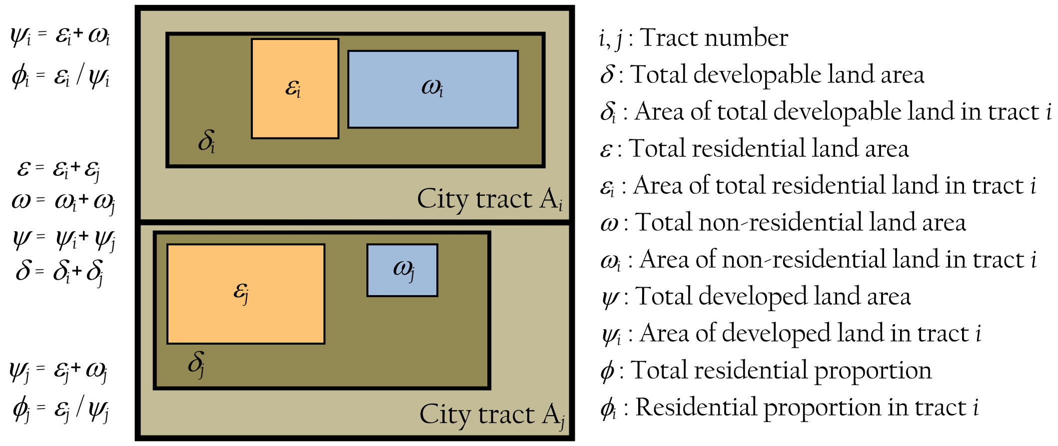


Figure 4.1: Identifiers of spatial components used in estimating sprawl indicators

4.1 AVERAGE DENSITY

As mentioned in Section 3.1, density is one of the most common measurements used in urban planning. Average density and density gradient will be elaborated in this section.

4.1.1 AVERAGE LAND-USE DENSITY (ALD)

In general, this density measure is based on the measurement of specific activities for a given unit area. The delicate part in calculating land-use density is taking land areas that have no potential for development out of the calculation in defining the denominator. Apart from the obvious case of water bodies, beaches, dunes, bare rocks, glaciers, marshes, peat bogs or intertidal flats, this study did not combine road and rail networks and their associated land when computing the denominator of this density.

Another critical point is what kind of land uses should be applied in representing density. There is no common agreement on what characterises the best definition of density for population, housing units, employment, and so on (Torrens & Alberti 2000). However, average land-use density (ALD) can be defined as

$$\text{ALD} = \frac{\psi}{\delta}, \tag{4.1.1}$$

and this will be adopted and tested in this study. Instead of using population density or the area of buildings, two-dimensional polygons of developed footprints are used in the calculation as mentioned earlier in Section 1.3.

4.2 DENSITY GRADIENT

The main idea of the density gradient is to gauge how density decreases when distance from a selected centre is increasing. It indicates how far people have located themselves towards the city fringe. The work of the urban economists dating from von Thunen relating to the rationale for economic densities, implicitly reveals that the density declines when the distance from its economic market centre increases (Batty & Kwang 1992). In general, when plotting calculated density versus determined distance from a designated centre, the slope of the anticipated linear relationship between them (when the relationships is transformed to linear form) is the density gradient. Lower density gradients imply greater degrees of decentralisation.

The centroid of a city is identified by weighting its two-dimensional shape based on all the tracts or polygons defining its extent. In this study, distances between a city's centroid and the geometric centroid of each subjected polygon which defines the area associated with the density are calculated and two kinds of polygon centroid are used in estimating this indicator. The first one is weighted by only residential land while the other is weighted by urbanised land. However, different specification of these functions lead to different rates of density decline. Here we will use the inverse power function and negative exponential functions to explore these density relationships.

4.2.1 Density Gradient: The Inverse Power Function (DGI)

The inverse power function uses two parameters to fit the distance decay and its mathematical structure is

$$\rho_x = \rho_0 \cdot x^{-\alpha}, \qquad (4.2.1\,a)$$

where ρ_x denotes the density of relevant activities e.g., population or particular land uses at distance x, while ρ_0 denotes the density at the city centre or core sometimes called the central business district (CBD). The distance decay parameter is denoted by α. Analysing the first derivative of the above function generates the value of $-\alpha$ as follows:

$$\frac{d\rho_x}{dx} = -\alpha \cdot \rho_0 \cdot x^{-\alpha-1}, \qquad (4.2.1\,b)$$

or

$$\frac{d\rho_x}{dx} = -\alpha \cdot \rho_0 \cdot x^{-(\alpha+1)}, \qquad (4.2.1\,c)$$

which is equal to

$$\frac{d\rho_x}{dx} = \frac{-\alpha \cdot \rho_0}{x^{\alpha+1}}, \qquad (4.2.1\,d)$$

or

$$\frac{d\rho_x}{dx} = \frac{-\alpha \cdot \rho_0}{x^{\alpha} \cdot x}. \qquad (4.2.1\,e)$$

From equation (4.2.1 *e*), this leads to

$$\frac{d\rho_x}{dx} = \frac{-\alpha}{x} \cdot \frac{\rho_0}{x^{\alpha}}, \tag{4.2.1f}$$

or

$$\frac{d\rho_x}{dx} = \frac{-\alpha}{x} \cdot \rho_0 \cdot x^{-\alpha}. \tag{4.2.1g}$$

From equation (4.2.1 *a*), using $\rho_x = \rho_0 \cdot x^{-\alpha}$ gives

$$\frac{d\rho_x}{dx} = \frac{-\alpha}{x} \cdot \rho_x, \tag{4.2.1h}$$

and then

$$\frac{d\rho_x}{\rho_x} = -\alpha \cdot \frac{dx}{x}. \tag{4.2.1i}$$

This gives

$$-\alpha = \frac{\frac{d\rho_x}{\rho_x}}{\frac{dx}{x}}. \tag{4.2.1j}$$

The value of $-\alpha$ can be interpreted as the ratio of the percentage change in density to the percentage change in distance from the city's centre which is essentially the elasticity of density with respect to distance The density gradient using the inverse power function (DGI) is equal to the value of α, that is

$$\text{DGI} = \alpha, \tag{4.2.1k}$$

and this is our key measure.

4.2.2 DENSITY GRADIENT: THE NEGATIVE EXPONENTIAL FUNCTION (DGN)

Base on the work of Clark (1951) who argued that as population densities are always finite at the core of the city, then the population density at distance x (ρ_x) from the city's centre falls according to the negative exponential function:

$$\rho_x = \rho_0 \cdot \exp(-\lambda x) = \rho_0 \cdot e^{-\lambda x}. \qquad (4.2.2\ a)$$

As mentioned before in the case of using the inverse power function, ρ_x denotes the density of relevant activities at distance x, while ρ_0 denotes the density at the city centre. Moreover, in this mathematical structure, $-\lambda$ is the distance decay parameter appearing as the rate of change in the negative exponential and as above in the case of the inverse power function, its value can be derived by analysing the first derivative of such function:

$$\frac{d\rho_x}{dx} = -\lambda \cdot \rho_0 \cdot e^{-\lambda x}. \qquad (4.2.2\ b)$$

From equation (4.2.2 *a*) where $\rho_x = \rho_0 \cdot e^{-\lambda x}$, this gives

$$\frac{d\rho_x}{dx} = -\lambda \cdot \rho_x, \qquad (4.2.2\ c)$$

and thus

$$-\lambda = \frac{d\rho_x}{\rho_x} \cdot \frac{1}{dx}, \qquad (4.2.2\ d)$$

which implies that λ is the percentage change in density for a small change in distance from an urban core. The DGN is equal to the value of λ,

$$\text{DGN} = \lambda. \qquad (4.2.2\ e)$$

In this study, we obtain the values of α and λ by plotting the calculated density versus the determined distance from the designated centre. In our applications, we will do this through the power and exponential curve-fitting functions in MATLAB©, where the values of α and λ can be estimated as the form of the slopes of the generated curve expressing the relationship between density and its distance to the city centre.

In general, when applying the inverse power function to identify the density gradient, a curve with sharply inclined head and flat long tail is generated, and these are shown as the solid lines in Figures 4.2(a) and (b). The straight lines, represented by the dashed lines in Figures 4.2(a) and (b), are obtained when using the negative exponential function in identifying the density gradient.

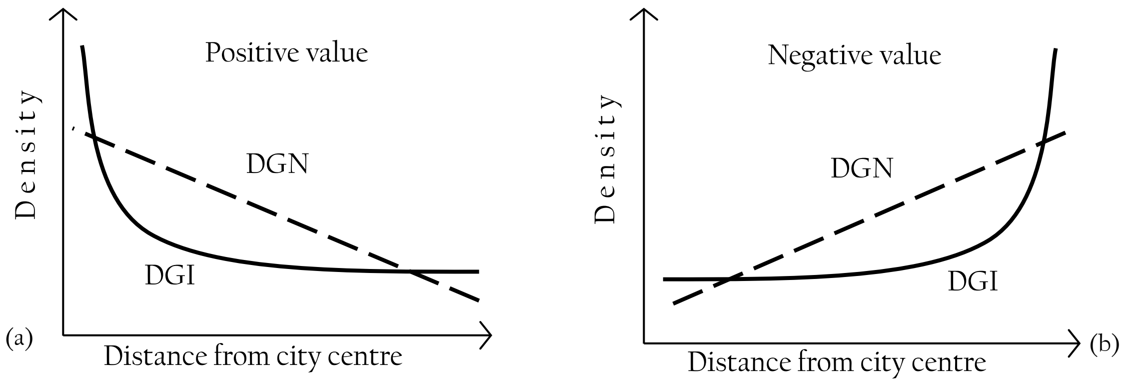


Figure 4.2: Comparison of conceptual graphs of DGI and DGN in the case of positive (a) and negative values (b) (adopted from Batty and Kwang 1992)

Both α and λ have no minimum or maximum values. The concept of the average density suggest that lower densities imply sprawling development; likewise as the values of α and λ approach zero, there is less difference between the density in the city centre and the fringe. In contrary manner, as the values of α and λ move away from zero, the difference in the densities between the centre and the fringe get greater. Consequently, higher positive values of α and λ mean that the density is high in the centre but low in the periphery, and these are represented by the dashed lines in Figures 4.3(a) and (b), while larger negative values of α and λ mean that density is low in the centre but comparatively high on the outside edge of the city (as represented by the dashed lines shown in Figures 4.4(a) and (b)).

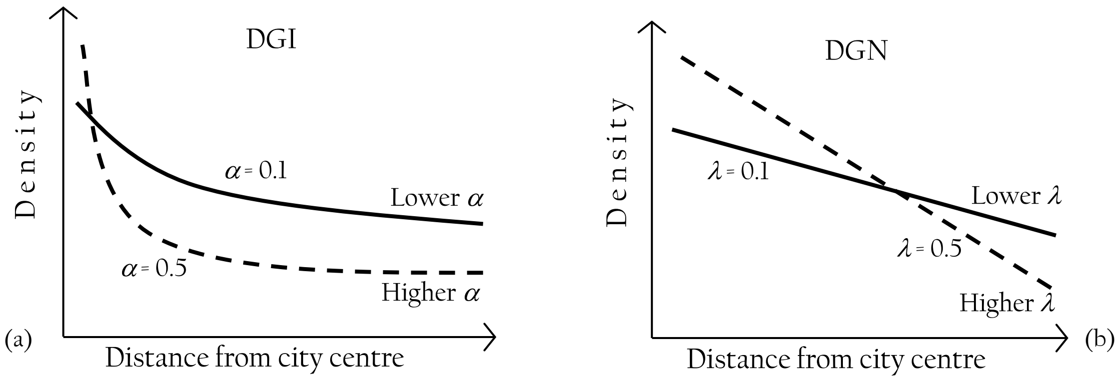


Figure 4.3: Comparisons between lower and higher values of positive α (a) and λ (b)

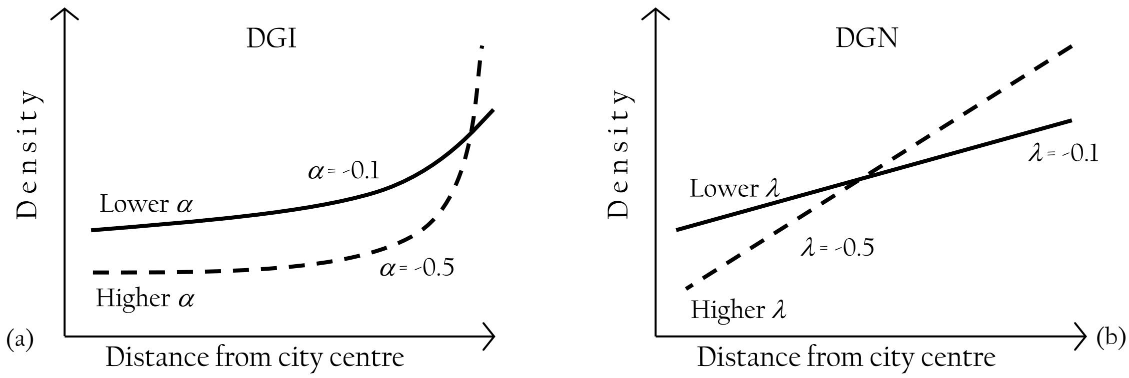


Figure 4.4: Comparisons between lower and higher values of negative α (a) and λ (b)

One classical way to measure the density gradient is by fixing a series of concentric rings over the observed area (Guerois & Pumain 2008). Another technique is by overlaying the land-use map as a grid square tessellation across the urban landscape. The comparison between both techniques depends on the fact that the ring thickness and grid size are determined arbitrarily. The black circles in Figures 4.5(a) and (c) represent the city centroids and in Figure 4.5(a), the three concentric rings with radiuses of 5, 10 and 15 kms are used to cover the whole city. With these values, the smallest ring covers $\pi(5)^2$ or about 78.57 km^2, while the largest ring covers $\pi(15)^2$ or 707.14 km^2. Three values of the density in relation to this circular pattern are computed according to the distance away from the centre e.g., at distances of 5 km, 10 km and 15 km.

In the case of analysing the grid shown in Figure 4.5(c), boxes with the size of 10x10 km^2 are used, and it needs eight such boxes to cover the entire city which is 800 km^2.

The small black dots symbolise centroids of subareas in each box. For ease of explanation, numbers in each subarea follow their distances to the city centre, where 1 signifies the shortest and 8 denotes the longest. Then, based on the square pattern, density is computed and plotted on the graph shown in Figure 4.5(d). When computing density at a certain distance x from the centre, any subareas that are closer to the centre than x will be included in the calculation. In the instance where the distance from the centroid of subarea 4 to the centre is 9.84 km, when computing the density at the distance of 9.84 km from the centre, subareas 1, 2 and 3 will be taken into the calculation along with subarea 4.

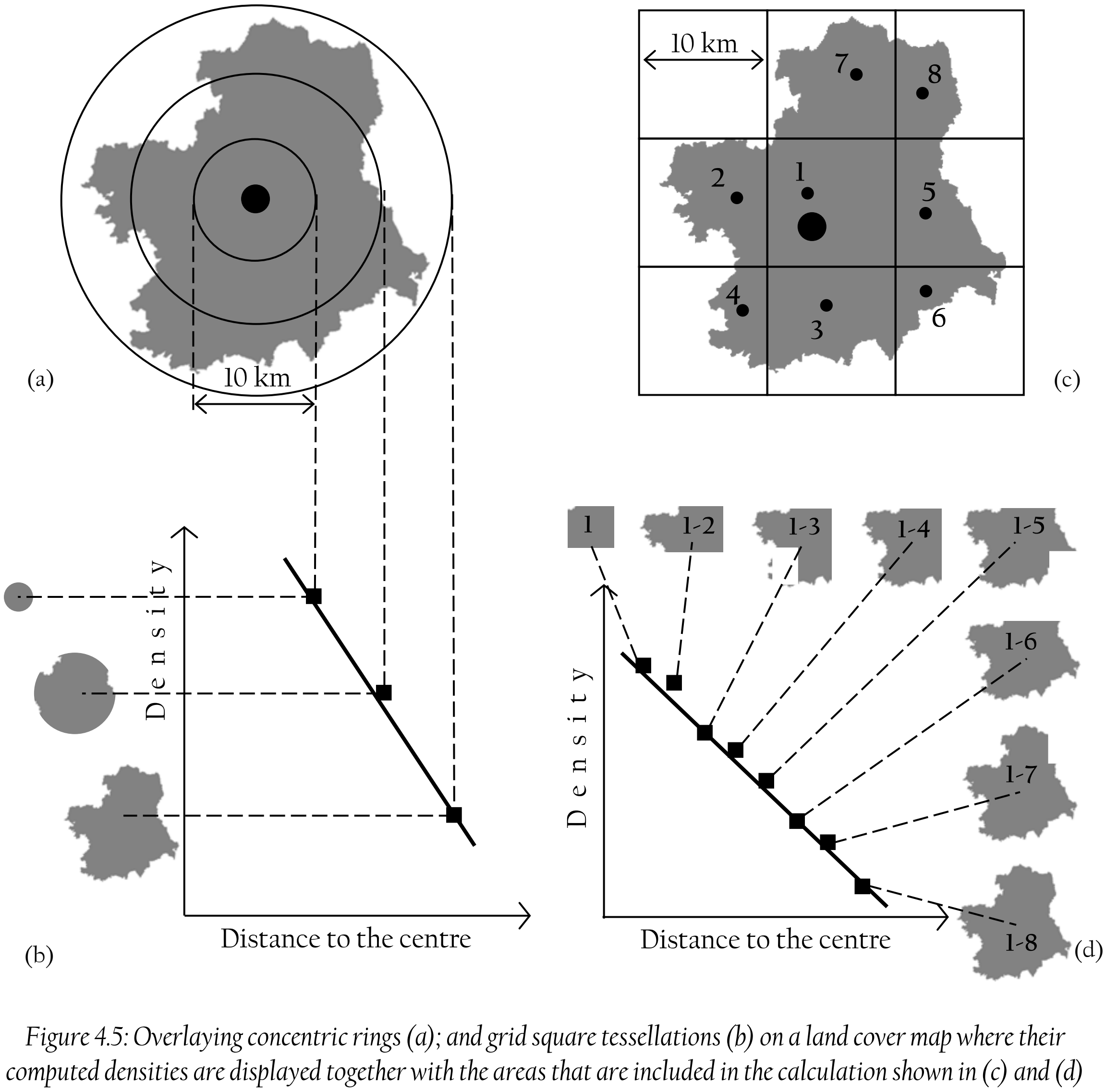


Figure 4.5: Overlaying concentric rings (a); and grid square tessellations (b) on a land cover map where their computed densities are displayed together with the areas that are included in the calculation shown in (c) and (d)

Two points must be emphasised here. First, applying concentric rings to the analysis of density is grounded in the notion that density decreases in concentric fashion similarly in every direction from the centre of the city, while the case of superimposing a grid on a two-dimensional digitised land cover map does not assume that space is homogeneous and isotropic. This can be seen when comparing the shapes of the cities that are used in the calculation of the density gradients shown in Figures 4.5(b) and (d). Second, with roughly equivalent covered areas, applying concentric rings to the analysis gives 3 samples of data, represented by small black squares, while 8 samples of data are obtained in the case of employing grid squares as in Figures 4.5(b) and (d)). Even the box size is subjectively chosen; however, the distance parameters used in computing density do not depend in a straightforward way on the box size, and each calculated distance from a centroid to another centroid are not forced to be positive integers. The latter technique allows density to be computed at more locations from the centre which means more sampling data, and various positive non-integral values will be fed into the calculations. Hence, rather than using concentric rings, the technique of the integrated grid square is used in analysing density gradient by virtue of the aforementioned advantages. Applying such a technique also benefits in testing the stability of potential sprawl indicators as we will explore later in Chapter 6.

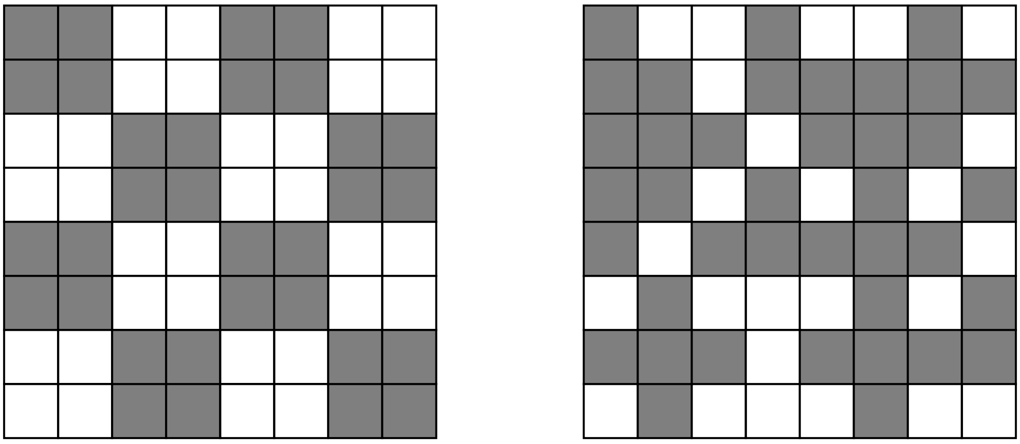
4.3 COMPLEXITY

This study uses digitised land-cover maps as the basis for analysing the degree of sprawl based on this quantitative approach. The city fills up its two-dimensional space, and from the top down, polygons defining the resolution of the land uses are generated. Even these polygons are only approximations to the real objects of study but they do provide the basic set of parameters that are useful in describing the character of complexity in quantitative way which includes the area and the perimeter of each polygon. The analysis of the perimeter-area ratio and the fractal dimension will now be reviewed.

4.3.1 The Perimeter-Area Ratio (PAR)

The PAR simply takes the complexity and shape of the patches into account in the form of borders between different types of land use (P_i) divided by size of the reference unit (A_i). The formula for PAR is

$$\mathrm{PAR} = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} A_i}. \qquad (4.3.1)$$



(a) PAR = 48/32 = 1.5 PAR = 74/32 = 2.3125 (b)

Figure 4.6: Examples of two different distributions of the same amount of residential land over the same amount of developable land providing different degrees of PAR

Figures 4.6(a) and (b) exhibit two examples of distributions over the same area for a similar amount of residential land area (32 grey squares) while the white squares signify non-residential land. For ease of explanation, the size of each square is 1x1 m^2. The border length of example (a) is shorter than (b), so different degrees of PAR are obtained.

4.3.2 THE FRACTAL DIMENSION (FD)

In general, fractals refer to self-similar patterns which may be exactly the same at every scale or statistically self-similar at different scales (Mandelbrot 1982). Mandelbrot popularised the term fractal in 1975 in his book titled *Les Objets Fractals: Forme, Hasard et Dimension*, and its English translation, *Fractals: Form, Chance and Dimension*, was published two years later (Mandelbrot 1977). The study of fractals expanded into the realm of computer-based modelling in the last 25 years. In particular, computers graphic applications of this geometry provided high realism in measuring two and three dimensional shapes. Moreover, fractal geometry was invented as a means to scrutinise shapes that are correlated over different spatial scales to differing degrees.

Many mathematicians in the century before Mandelbrot laid down the fundamental ideas for his work in developing the concept of fractals. In 1918, Felix Hausdorff developed the 'Hausdorff dimension' which allows for sets to have non-integer dimensions, opening the way to the introduction of one of the main parameters of fractal geometry, the *fractal dimension* (Cox & Wang 1993).

Mandelbrot referred to previous work by Lewis Fry Richardson who demonstrated that a coastline's length inversely changes with the length of the measuring stick used; the smaller the measuring stick, the longer the total length of the measured coastline (as we show in Figure 4.7). Based on such a notion, the fractal dimension of a coastline quantifies how the number of scaled measuring sticks required in estimating the coastline changes with the scale applied to the stick. It should be noted that there are various formal mathematical definitions of fractal dimension that are based on this conception involving the way changes in detail change with scale (Mandelbrot 1967).

It is obvious that the length of the coastline (L) is inversely proportional to the measuring unit (U), and therefore the fractal dimension can be understood through the scaling rule:

$$-FD = \frac{\log L}{\log U}, \qquad (4.3.2\ a)$$

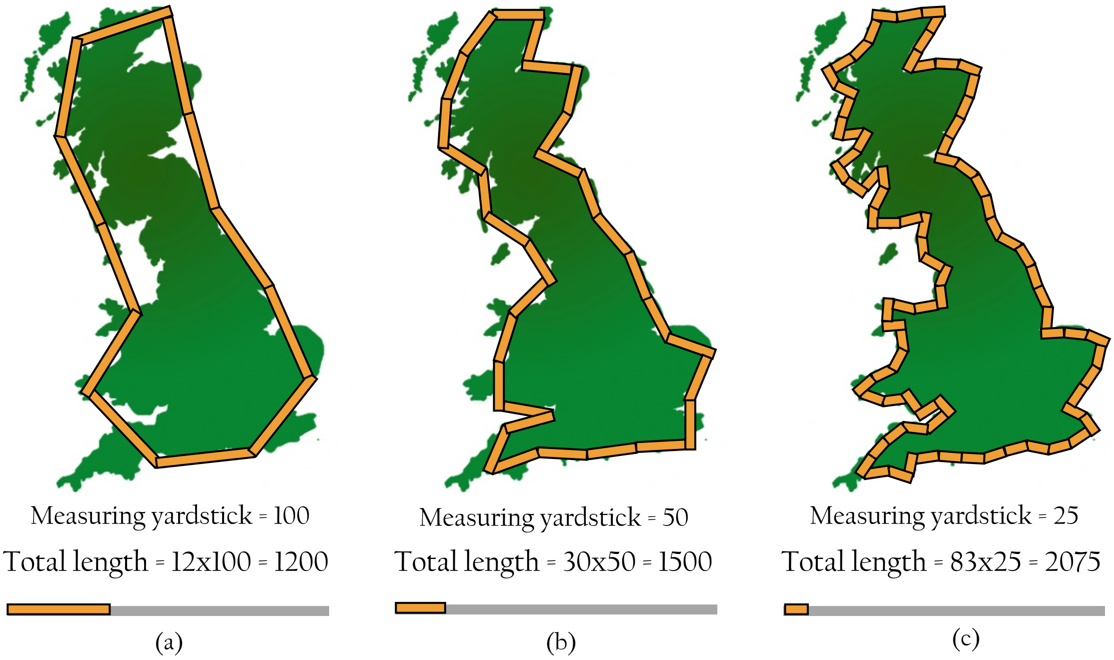


Figure 4.7: The total length of Great Britain's coastline increases when the length of the measuring yardstick is scaled smaller and smaller, from (a) to (b) and to (c)

Another simple way to understand the derivation of the fractal dimension can be seen when plotting the total length of the coastline on the y-axis and the length of the ruler used on the x-axis, where the logarithms of both sets of data show a linear relationship between them (as in Figure 4.8). The fractal dimension can be computed from the slope of the so-called *Richardson plot*, the straight line which best fits the data (Cox & Wang 1993). Mandelbrot assigned that the fractal dimension as one minus the slope of the linear relationship found (1 - slope) and demonstrated that 1.22 is the fractal dimension of the west coast of Britain. In general, the rougher the coastline, that is the more indented the steeper the slope, and hence the larger the fractal dimension, with coastlines that are highly convoluted having dimensions nearer 2 in comparison with smooth, non-indented coastlines whose dimension is nearer 1.

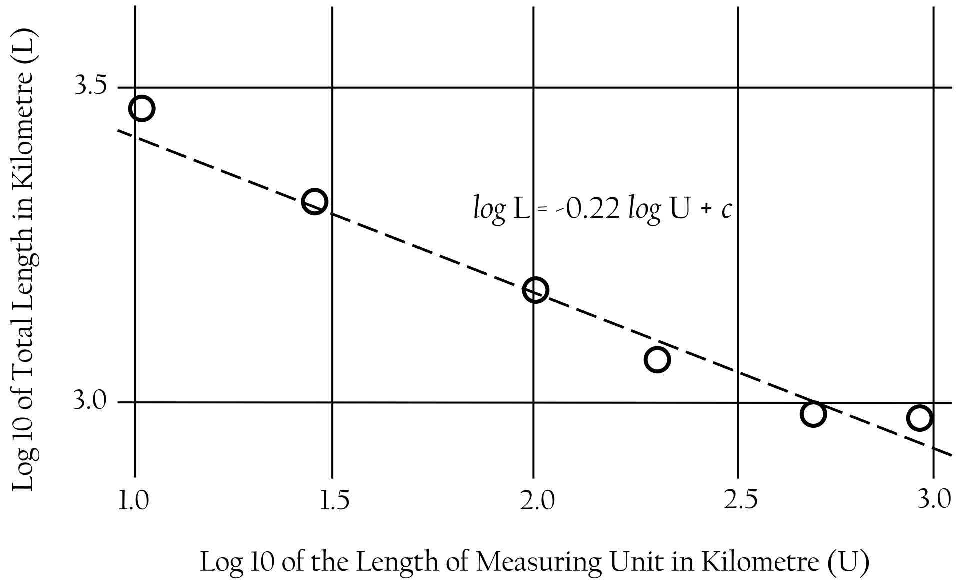


Figure 4.8: Richardson's data on measuring the length of the west coast of Britain. The small circles signify the total measured length which tends to approach a limit when the measuring unit decreases to zero (adopted from Mandelbrot 1967)

For sets describing common geometric forms, the theoretical fractal dimension is equal to the set of topological or Euclidean dimension. Therefore, it is 0 for sets expressing points (0-dimensional sets); 1 for sets describing lines (1-dimensional sets having length only); 2 for sets depicting filled squares (2-dimensional sets having length and width); and 3 for sets portraying volumes (3-dimensional sets including length, width and height). If the theoretical fractal dimension of a set exceeds its Euclidean dimension, the set is considered to be fractal, that is, have fractal geometry. Consequently, the fractal dimension can take non-integer values, illustrating that a set fills its space in a different way from the set of ordinary planar geometry. Consequently, the fractal dimension can fill the gap that classical geometry is incapable of measuring with this fractal geometry being highly relevant to describing many natural and man-made forms. In other words, fractal dimension can be used as an index for measuring the complexity of spatial patterns (Lam & Cola 1993). Fractal dimension can also provide a description of how space is occupied by a particular shape (Cox & Wang 1993) or as a measure of the complexity of the spatial patterns.

In general, there are 7 methods for calculating the fractal dimension of two-dimensional surfaces and these are the: 1) divider method, 2) box method, 3) triangle method, 4) slit-island, 5) power spectral method, 6) variogram method and 7) size distribution method. The first four methods require straightforward measurement of the length of a boundary and the measurement of an area based on their simple geometrical pattern. Rather than analysing the vertical profile, the box method and slit-island method analyse horizontal profiles which are more suitable for the examination of land cover data.

The other three methods relate to a functional representation of variability. The power spectral method is mainly appropriate for analysing time series data which is not relevant to this study. Counting on statistical techniques as their basis, the variogram method and size distribution method plot the semi-variance against the number of counted objects greater than the size class on the y-axis and x-axis respectively. However, the ambiguity in the arbitrary establishment of the size class interval required in both methods affects the value of the fractal dimension. Moreover, the equation used in deriving the fractal dimension is not a trivial issue since it varies according to types of the variable distributions such as area, particle density, and so on (Cox & Wang 1993). Consequently, we have decided that using the box method and slit-island method in calculation for the fractal dimension is the most straightforward and least ambiguous.

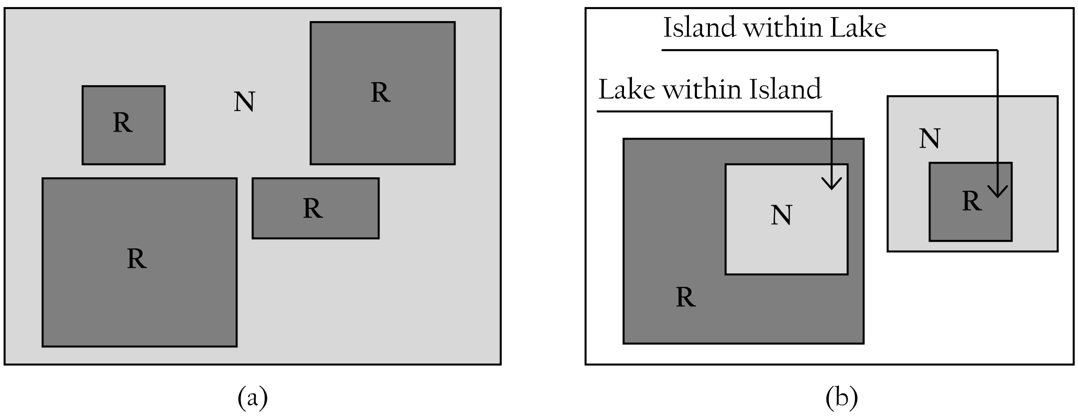


Figure 4.9: Surface created when using the Slit-island method: the 'island' of residential land use (the dark grey regions) are denoted by R and the 'lake' of non-residential land use (the bright grey regions) denoted by N, (a); with the 'island within lake' and 'lake within island' (b)

The slit-island analysis was initially introduced by Mandelbrot et al. (1984). When the surface is sliced horizontally, it classifies the surface into two categories: 1) the 'island' (residential land use) and 2) the 'lake' (non-residential land use) which appear above and below the water, correspondingly (as we show in Figure 4.9(a)). Areas and perimeters of islands are measured, and then plotted on a log-log plot respectively. In the case where their patterns form straight lines, the fractal dimension using the slit-island method (FDS) is equal to 2/slope. Compared with Mandebrot et al.'s test (1984), using ArcMap10©, we were able to define the aforementioned parameters both in the case of 'lakes within islands' and 'lakes within islands' (as we show in Figure 4.9(b)).

Also based on the scaling rule, the box method evaluates how many same sized square boxes, defined by the length of a side of the square, are needed to cover the object of interest. This can be done by defining the boxes in a square grid, then by counting the number of intersections of the object with the boxes. The number of boxes it takes to cover an object changes when the grid size changes are then noted at each scale as we show in Figure 4.10.

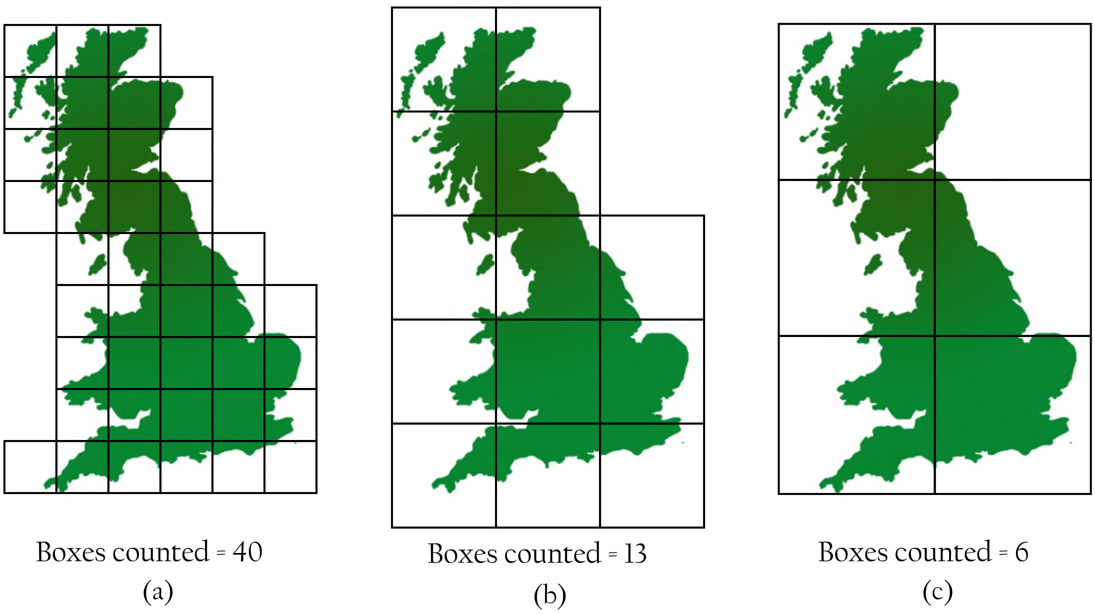
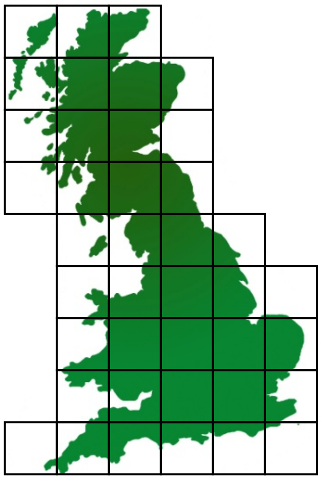


Figure 4.10: Increasing the box size from (a) to (b) and to (c) result in decreasing the number of boxes needed to cover the same 2-dimensional image

Reiterating the process with different sizes of box will result in a logarithmic function of 1/box size (which we plot on the x-axis) versus log of the number of boxes needed to cover the object on the y-axis. The fractal dimension calculated by using box method (FDB) is equal to the slope of this plot.

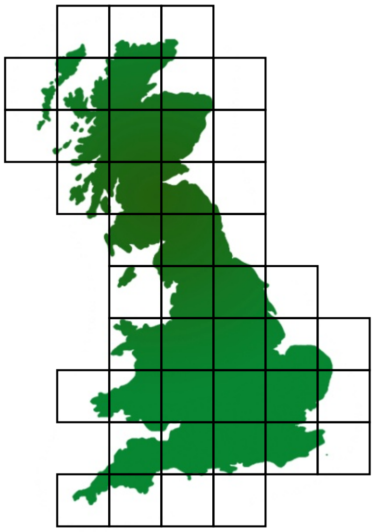
In this study, FDB is calculated by using the software called FracLac, a plugin for ImageJ. Black and white digitised images are required in the FracLac analysis and this software uses the average amount of defined foreground pixels per box at any particular size for calculating fractal dimension (as we show in Figure 4.11). Superimposing the same image with the same calibre of grid, we can place the boxes at different positions and this affects the number of boxes needed to cover the entire object e.g., fourteen boxes are defined in Figure 4.12(a) and seven boxes in Figure 4.12(b).

Figure 4.11: On black background, the FracLac programme has computed the FDB of the object (white-coloured polygons) exhibiting the polygons of residential land of the Berlin metropolis



Number of boxes needed to cover the image = 40

(a)



Number of boxes needed to cover the image = 44

(b)

Figure 4.12: Difference in the number of boxes needed to cover the image occurs when laying the same box size over the same image but at different locations

Only for the first location which is fixed at the top left of the bounding box, FracLac analysis is able to perform multiple scans at random orientations where x-y coordinates are randomly generated within the largest box size defined from the series of grid calibres. When a series of box sizes are applied at multiple locations, the average FDS values are calculated. Assigning more sampling orientations in the analysis generates a greater chance of finding a more efficient covering but slows the scan process and is costly with respect to longer times in computation. This study uses a default of 4 different orientations.

The range of box sizes can also affect the results. In setting the minimum box size, 1 pixel is a logical lower limit since the regression line intersects the y-axis at the log of the number of pixels of the image, where the log(1) = 0, can be plotted. By default, FracLac sets the maximum box size at 45% of the resolution of the image as its standard. Then, the average FDB will be computed based on all of the combinations of grid positions and box sizes used in scanning the object. FracLac also produces a better result with a facility for removing the sequences of 'no change in the regression line' out of the analysis.

In general, the basic difference between the calculations for FDS and FDB is that the box method stresses the measurement of all of the shapes at different scales, while the slit-island method assumes that the size distribution of the population of shapes echoes the degree of self-similarity. However, when analysing two-dimensional surfaces defining urban systems, the fractal dimension of any development should range from 1 to 2; all the way from land uses that fill up more than the linear coverage, where the fractal dimension is equal 1, to surfaces that fill less than the entire two-dimensional space in which they exist (Mesev et al. 1995). For landscapes that are composed of simple geometric shapes like squares or rectangles, the fractal dimension will be small, approaching 1; on the contrary, for landscapes that contain many plots of land uses and also complicated shapes, the fractal dimension will be large and close to the value of 2 (O'Neill et al. 1988). Torrens & Alberti (2000) suggested that as the value of fractal dimension gets close to 1, the form of development implies scattered development and vice versa but there is the possibility that highly scattered development has a fractal dimension less than 1 reminiscent of what Mandelbrot (1977) calls a 'fractal dust'.

4.4 CLUSTERING

In terms of residential segregation, the conceptual differences between the concepts of clustering versus concentration and centralisation have been explained by Massey & Denton (1988). Slightly adjusting their example to match the situation of land-use distributions, let us assume that two urban metropolitan areas have the same amount of residential land and non-residential land-use proportions. There is no residential land-use mixing with other land uses. Moreover, all residential polygons are of identical size locating at the same average distance from the city centre. This means that both cities would display similar degrees of evenness, concentration, exposure, and centralisation. The distinction as to how the residential polygons locate themselves with respect to each other in both cases is the key issue in defining the degree of clustering. If all residential polygons in one area were adjacent to one another, while in the other area they were totally disconnected from each other, then the former would be considered to be more isolated than the latter.

The purpose of the degree of clustering is to measure the extent to which elements or activities of interest are randomly distributed or clustered. The measure of clustering focuses on the spatial distribution of the relevant land use with respect to one another. Theoretically, a higher level of clustering means that residential land use, or polygons defining built up areas according to this study, adjoin or strongly group with one another, forming a single large precinct of residential or developed land. The lowest degree of clustering implies a 'checkerboard problem' (White 1983) where polygons of residential or built-up land are dispersed similar to black squares on a checkerboard (Massey & Denton 1988). Related statistics such as Moran's I, the Geary Coefficient, the Index of Absolute Clustering, the Index of Spatial Proximity, and the Index of Relative Clustering measure these characteristics and will now be reviewed in this section.

4.4.1 Moran's I Coefficient (MORAN)

Moran's Coefficient is widely used as it is one of the classic spatial autocorrelation statistics which measures and analyses the degree of dependency among observations in a geographical space. MORAN's I can be calculated as

$$\text{MORAN} = \frac{n \cdot \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(\varepsilon_i - \frac{\varepsilon}{n}\right)\left(\varepsilon_j - \frac{\varepsilon}{n}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij} \cdot \sum_{i=1}^{n}\left(\varepsilon_i - \frac{\varepsilon}{n}\right)^2}, \qquad (4.4.1)$$

where, n is the number of residential polygons, and all other definitions are as in Figure 4.1. The intensity of the geographic relationship between observations in an environment is denoted by W_{ij}. This is an element of a matrix of spatial weights which generally can be obtained through the 'contiguity matrix' that is equal to 0 when unit i and j are spatial disconnected, and is equal to 1 otherwise. Generating a large (n x n)

contiguity matrix involves visual inspection of maps which can be very time and resource consuming (Massey & Denton 1988). Using the notion that the influence of the surrounding areas swiftly decreases with the distance away from the observed target point or polygon, in defining W_{ij}, this study uses the negative exponential of the distance between the centroids of polygons i and j, defined as $\exp(-d_{ij})$.

4.4.2 THE GEARY COEFFICIENT (GC)

Another classic spatial autocorrelation statistic that is commonly used is Geary's Coefficient. Its formula when analysing residential land use and urbanised land is

$$GC = \frac{(n-1)\cdot \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(\varepsilon_i - \varepsilon_j\right)^2}{2\cdot \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij} \cdot \sum_{i=1}^{n}\left(\varepsilon_i - \frac{\varepsilon}{n}\right)^2}, \qquad (4.4.2\ a)$$

Where GC is conceptually similar to MORAN's I, except that the former focuses on the deviations from the mean rather than the deviations of each observed polygon relative to one another. Moreover, in order to maintain similar scaling with that of MORAN, the Adjusted Geary,

$$GC' = -\left(\frac{(n-1)\cdot \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(\varepsilon_i - \varepsilon_j\right)^2}{2\cdot \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij} \cdot \sum_{i=1}^{n}\left(\varepsilon_i - \frac{\varepsilon}{n}\right)^2} - 1\right), \qquad (4.4.2\ b)$$

is suggested since the GC's minimum and maximum values are 0 and +2. Both MORAN and the adjusted GC' coefficients then vary from -1 to +1. Randomly scattered development is represented when this value gets close to zero. Positive values approaching +1 mean that the closely associated elements are closely clustered, while negative values approaching -1 indicate that neighbouring values are more dissimilar than expected by chance, suggesting a spatial pattern similar to a chess board.

4.4.3 THE INDEX OF ABSOLUTE CLUSTERING (ACL)

Different from the previous two indices, the ACL estimates the degree of clustering based on characteristic comparisons between subareas. Drawing on Dacey's (1965) and Geary's (1954) work, Massey & Denton (1988) developed the Index of Absolute Clustering, which is defined as:

$$\text{ACL} = \frac{\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{\varepsilon_i}{\varepsilon}\cdot W_{ij}\cdot\varepsilon_j\right)-\left(\frac{\varepsilon}{n^2}\cdot\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}\right)}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{\varepsilon_i}{\varepsilon}\cdot W_{ij}\cdot\psi_j\right)-\left(\frac{\varepsilon}{n^2}\cdot\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}\right)}. \tag{4.4.3}$$

The maximum value of ACL approaches but never gets to +1.0 and this represents more clustered development, while totally randomly dispersed development (the checkerboard pattern) is represented by the minimum value of zero.

4.4.4 THE INDEX OF SPATIAL PROXIMITY (ISP)

The Index of Spatial Proximity (ISP) was proposed by White (1986) and this starts with the calculation of the average proximity between elements of a similar group (residential polygon related to one another),

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{W_{ij}\varepsilon_i\varepsilon_j}{\varepsilon^2}, \tag{4.4.4 a}$$

and between members of the other group (between non-residential polygons),

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{W_{ij}\omega_i\omega_j}{\omega^2}. \tag{4.4.4 b}$$

Then, the average proximity among all members is estimated in the same fashion as

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{W_{ij}\psi_i\psi_j}{\psi^2}. \tag{4.4.4 c}$$

Weighted by the component of each group of land uses,

$$\text{ISP} = \frac{\left(\varepsilon \cdot \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{W_{ij}\varepsilon_i\varepsilon_j}{\varepsilon^2}\right) + \left(\omega \cdot \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{W_{ij}\omega_i\omega_j}{\omega^2}\right)}{\psi \cdot \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{W_{ij}\psi_i\psi_j}{\psi^2}}, \qquad (4.4.4\ d)$$

the ISP is the average of intra-group propinquity. When the level of clustering between residential and non-residential land uses is equal, the ISP gives the value of +1. The index will be greater than +1 when each land use locates closer to one another than each other. When members of a group locate closer to members of the other group than to members of their own group, the ISP would be less than +1.

4.4.5 THE INDEX OF RELATIVE CLUSTERING (RCL)

Massey & Denton (1988) developed White's ISP into the Index of Relative Clustering which is defined as

$$\text{RCL} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{W_{ij}\varepsilon_i\varepsilon_j}{\varepsilon^2}}{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{W_{ij}\omega_i\omega_j}{\omega^2}} - 1. \qquad (4.4.5)$$

The main idea of the RCL is to compare the average proximity between residential land use with the average distance between non-residential land use. From the equation of RCL, positive values occur when residential land use exhibits a larger degree of clustering than of non-residential land use and vice versa. When both land-uses display the same extent of clustering, the RCL gives a value of zero.

4.5 CENTRALISATION

The degree of centralisation is the extent to which a group of activities or land uses spatially locates close to the urban centre. Among proposed indicators of centralisation, the ratio between the amount of land in a given group that locates within the city centre and the amount of such a group that locates in the entire metropolitan area is broadly reported. However, the estimation of such indices and similar ones that require the boundary of the city centre to be defined have a major drawback since the boundary of a city centre is often politically defined rather than a social or natural subdivision of the space. Central cities that were established before have been surrounded by suburbs and continue to expand or get smaller. The relative size of the central city through time is therefore a function of the period in which the city developed and this does not reflect a real sense of a group's centralisation. In this section, we will review the Absolute Centralisation Index and the Relative Centralisation Index.

4.5.1 THE ABSOLUTE CENTRALISATION INDEX (ACE)

With the recognition of the limitations of the aforementioned indicators of centralisation, social scientists have proposed other indicators of centralisation that make more use of spatial data. The Absolute Centralisation Index,

$$\text{ACE} = \left(\sum_{i=1}^{n} \frac{{}_{d}\varepsilon'_{i-1}}{{}_{d}\psi'_{i-1}} \cdot \frac{{}_{d}\delta'_{i}}{\delta}\right) - \left(\sum_{i=1}^{n} \frac{{}_{d}\varepsilon'_{i}}{{}_{d}\psi'_{i}} \cdot \frac{{}_{d}\delta'_{i-1}}{\delta}\right), \qquad (4.5.1)$$

measures spatial distribution of residential land use relative to the distribution of developable land around the centre of the city. When *n* tracts are ordered by increasing distance from the centre of the metropolitan area, ${}_{d}\varepsilon'_{i}$ and ${}_{d}\psi'_{i}$ are the cumulative residential land and built-up land, respectively through the areal unit *i*. Hence ${}_{d}\varepsilon'_{i}/{}_{d}\psi'_{i}$ are the respective cumulative proportions of residential land use in tract *i* while ${}_{d}\delta'_{i}$ refers to the cumulative proportion of developable land area through tract *i*. How to obtain the value of ACE is conceptually shown in Tables 4.1, 4.2 and 4.3.

Table 4.1: An example of the city 'Z' with values of ε_i, ω_i, ψ_i, δ_i and its distance from the city centre of areal units Z_1 to Z_5

Areal Unit	ε_i	ω_i	ψ_i	δ_i	Distance from city centre
Z_1	6	2	8	10	59
Z_2	12	0	12	25	38
Z_3	4	8	12	20	21
Z_4	14	6	20	30	16
Z_5	6	4	10	15	4

Table 4.2: Areal units of the city 'Z' ordered by increasing distance from its city centre

Areal Unit	${}_d\varepsilon_i$	${}_d\omega_i$	${}_d\psi_i$	${}_d\delta_i$	Distance from city centre
Z_5	6	4	10	15	4
Z_4	14	6	20	30	16
Z_3	4	8	12	20	21
Z_2	12	0	12	25	38
Z_1	6	2	8	10	59
Total				100	

Table 4.3: Areal units of the city 'Z' ordered by increasing distance from its city centre with cumulative ε_i (${}_d\varepsilon'_i$), cumulative ψ_i (${}_d\psi'_i$), cumulative δ_i (${}_d\delta'_i$), the respective cumulative proportion of residential land use (${}_d\varepsilon'_i/{}_d\psi'_i$), and the cumulative proportion of developable land area (${}_d\delta'_i$/Total δ)

Areal Unit	${}_d\varepsilon'_i$	${}_d\psi'_i$	${}_d\delta'_i$	${}_d\varepsilon'_i/{}_d\psi'_i$	(${}_d\delta'_i$/Total δ)
Z_5	6	10	15	0.60	0.15
Z_4	20	30	45	0.67	0.45
Z_3	24	42	65	0.57	0.65
Z_2	36	54	90	0.67	0.90
Z_1	42	62	100	0.68	1.00

$$\sum_{i=1}^{n} \frac{{}_d\varepsilon'_{i-1}}{{}_d\psi'_{i-1}} \cdot \frac{{}_d\delta'_i}{\sum_{i=1}^{n}\delta}$$

$$\sum_{i=1}^{n} \frac{{}_d\varepsilon'_{i}}{{}_d\psi'_{i}} \cdot \frac{{}_d\delta'_{i-1}}{\sum_{i=1}^{n}\delta}$$

The value of ACE ranges from -1.0 to +1.0, with positive values illustrating that residential land use agglomerates close to the centre and negative values implying that residential land use scatters outside the city centre. A value of zero means that residential land use has the same level of distribution throughout the metropolitan area.

4.5.2 The Relative Centralisation Index (RCE)

While the ACE examines the extent of the absolute distribution of the extent to which residential land use is centralised, an equivalent measure expressing residential land use centralisation compared to non-residential land use can also be defined. The Relative Centralisation Index proposed by Duncan and Duncan (1955) is defined as

$$\text{RCE} = \left(\sum_{i=1}^{n} \frac{d\varepsilon'_{i-1}}{d\psi'_{i-1}} \cdot \frac{d\omega'_{i}}{d\psi'_{i}} \right) - \left(\sum_{i=1}^{n} \frac{d\varepsilon'_{i}}{d\psi'_{i}} \cdot \frac{d\omega'_{i-1}}{d\psi'_{i-1}} \right). \quad (4.5.2)$$

The order of *n* areal units and how to obtain the centre of the metropolitan area are managed in the same way as in the calculation of the ACE. Continued from Tables 4.1 and 4.2, Table 4.4 shows how to conceptually obtain the value of RCE for the city 'Z'.

Table 4.4: Areal units of the city 'Z' ordered by increasing distance from its city centre with cumulative ε_i ($_d\varepsilon'_i$), cumulative ψ_i ($_d\psi'_i$), cumulative δ_i ($_d\delta'_i$), and the respective cumulative proportion of residential land-use ($_d\varepsilon'_i/_d\psi'_i$)

Areal Unit	$_d\varepsilon'_i$	$_d\omega'_i$	$_d\psi'_i$	$_d\varepsilon'_i/_d\psi'_i$	$_d\omega'_i/_d\psi'_i$
Z_3	6	4	10	0.60	0.40
Z_4	20	10	30	0.67	0.33
Z_3	24	18	42	0.57	0.43
Z_2	36	18	54	0.67	0.33
Z_1	42	20	62	0.68	0.32

$$\sum_{i=1}^{n} \frac{d\varepsilon'_{i-1}}{d\psi'_{i-1}} \cdot \frac{d\omega'_{i}}{d\psi'}$$

$$\sum_{i=1}^{n} \frac{d\varepsilon'_{i}}{d\psi'_{i}} \cdot \frac{d\omega'_{i-1}}{d\psi'_{i-1}}$$

The RCE varies between -1.0 and +1.0. Negative values mean that residential land use disperses away from the centre of the metropolitan area and positive values indicate that residential land use locates relatively closer to the centre than non-residential land use. A score of zero indicates that two groups have the same spatial distribution around the centre. The RCE can be interpreted as the amount of the residential land that would have to relocate in order to match the extent of centralisation of non-residential land use

4.6 Evenness

Evenness refers to the differential distribution of a group of relevant activities or land uses or between groups of such types in an areal unit. Evenness is measured in a relative sense which is residential relative to non-residential development in this case. Evenness is minimised with a value of +1 when residential and non-residential lands do not share a common area. On the contrary, the degree of evenness of the city is maximised with the value of zero when every sub-unit has the same relative amount of residential and non-residential land as in the city as a whole. Another way to understand the concept of evenness is by expression through the Lorenz curve which plots the cumulative proportion of residential land use against the cumulative proportion of non-residential land use across areal units ordered from smallest to largest residential proportions. The degree of evenness is represented by the maximum vertical distance between the diagonal line of evenness and the generated curve as we show in Figure 4.12.

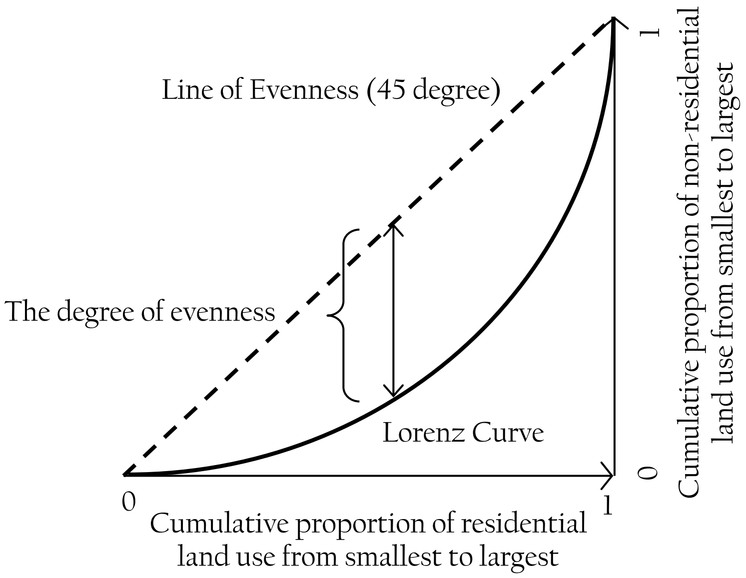


Figure 4.13: Explanation of the concept of 'evenness' through the Lorenz Curve

4.6.1 THE INDEX OF DISSIMILARITY (IOD)

The value of the IOD can be obtained by measuring the divergence from evenness by taking the weighted absolute mean difference of every unit's residential land use proportion from the city's residential development proportion. The index stands for the proportion of residential land that would have to relocate itself to achieve an even distribution. Moreover, this residential development that moves is being expressed as a proportion of the number that would have to move under conditions of an uneven distribution of residential development. Massey and Denton (1988) proposed one formula for the dissimilarity index which is

$$\text{IOD} = \sum_{i=1}^{n} \frac{\psi_i \left|\phi_i - \phi\right|}{2\psi\phi\left(1-\phi\right)}. \qquad (4.6.1\,a)$$

The equation of IOD needs to be adjusted, so its minimum and maximum values correspond to the meanings of other conceptual and operational dimensions of sprawl and the index thus becomes:

$$\text{IOD}' = 1 - \sum_{i=1}^{n} \frac{\psi_i \left|\phi_i - \phi\right|}{2\psi\phi\left(1-\phi\right)}. \qquad (4.6.1\,b)$$

The index ranges from 0, the most uneven distribution of residential land use, to +1.0, the minimum value which is an even distribution. When there is absolutely no residential land use mixing with non-residential land use in any subarea, the degree of IOD will be minimised to a value of zero. A smaller value of IOD thus implies homogeneity in the land-use mix. It should be noted that the degree of IOD will approach +1.0 when the difference in the level of land-used mix between a city and its subareas as a whole gets smaller.

4.6.2 THE GINI COEFFICIENT (GINI)

The Gini coefficient is a measure of statistical dispersion, universally used as a measure of inequality in the distribution of income or in the inequality of the wealth distribution. However, it can be used to measure any form of evenness or unevenness in any distribution. In the case of residential land use, the index is calculated from unordered size data as the mean absolute difference between every residential proportion weighted between every possible pair of subareas as can be seen from the formula proposed by Massey & Denton (1988):

$$\text{GINI} = \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{\psi_i\psi_j\left|\phi_i-\phi_j\right|}{\psi^2\phi(1-\phi)}. \tag{4.6.2 a}$$

Similar to the case of IOD, an adjustment in the GINI equation will aid in harmonising its minimum and maximum values to others and this can be achieved from:

$$\text{GINI}' = 1-\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{\psi_i\psi_j\left|\phi_i-\phi_j\right|}{\psi^2\phi(1-\phi)}. \tag{4.6.2 b}$$

The coefficient would register its maximum value at 1.0 for a city in which the residential proportion of every subarea is equal to the average residential proportion. On the contrary, it would register a coefficient of zero if residential and non-residential land do not share a single common subarea.

4.6.3 The Atkinson Index (AI)

The focal concept in measuring the degree of evenness is the transfer principle which also can be seen in the structure of the IOD, GINI and AI equations. Moreover, they are compositionally invariant, but unlike the IOD and GINI indices, through the shape parameter (μ), the AI allows researchers to determine how to weight the increments to unevenness contributed by different divisions of the Lorenz curve, over or under the average residential proportion. The formula for AI is adjusted as

$$\text{AI}' = \frac{\phi}{1-\phi}\cdot\left|\sum_{i=1}^{n}\frac{(1-\phi_i)^{1-\mu}\,\phi_i^{\mu}\psi_i}{\phi\psi}\right|^{\frac{1}{1-\mu}}, \tag{4.6.3}$$

in order to agree with the meanings of other indicators of 'evenness'. The coefficient of μ ranges from zero to one. When $0 < \mu < 0.5$, areal units where $\mu_i < \mu$ give a larger contribution to unevenness; whereas for $0.5 < \mu < 1$, areal units where $\mu_i > \mu$ are indicative of more unevenness. For $\mu = 0.5$, units of residential proportion which are over- and under-representations of supply contribute evenly to the calculated evenness degree. When the residential and non-residential lands do not share common subareas, AI achieves its minimum value at zero, while when each subarea's residential proportion is equal to the average residential proportion, AI will reach its maximum value of +1.0.

4.6.4 The Information Entropy Index (IEI)

The concept of entropy which is related to spatial distribution of a range of phenomena (Batty 1972) is also brought in to estimate the degree of evenness. Information entropy most widely used in spatial analysis is adopted from Shannon (1948) and its formula is

$$H(r) = -\sum_i p_i \cdot \ln p_i \qquad (4.6.4\ a)$$

where r is a discrete random variable while p_i is the probability of the event happening in the macro-state r_i. The most probable state refers to the event that diverse land-uses are evenly distributed across the entire areal space, and this maximises the information entropy at the value of ln$N$. Firstly, the city's entropy, in the case where there are only two land uses is

$$E = \left(\frac{\phi}{\sum_{i=1}^{n} \phi_i} \cdot \log \frac{\sum_{i=1}^{n} \phi_i}{\phi} \right) + \left(\left(1 - \frac{\phi}{\sum_{i=1}^{n} \phi_i} \right) \cdot \log \frac{1}{1 - \frac{\phi}{\sum_{i=1}^{n} \phi_i}} \right), \qquad (4.6.4\ b)$$

and this entropy is the degree of land-use distribution where every land use reaches its maximum extent, with a 50-50 division in the case of the city containing just two land uses. Secondly, the unit's entropy,

$$\mathrm{E}_i = \left(\frac{\phi_i}{\sum_{i=1}^{n} \phi_i} \cdot \log \frac{\sum_{i=1}^{n} \phi_i}{\phi_i} \right) + \left(\left(1 - \frac{\phi_i}{\sum_{i=1}^{n} \phi_i} \right) \cdot \log \frac{1}{1 - \frac{\phi_i}{\sum_{i=1}^{n} \phi_i}} \right), \qquad (4.6.4\ c)$$

can be computed. Finally, the IEI is calculated by weighting the average divergence of each unit's entropy from the city's entropy and this can be expressed as

$$\mathrm{IEI} = \sum_{i=1}^{n} \frac{\psi_i \left(\mathrm{E} - \mathrm{E}_i \right)}{\mathrm{E} \cdot \psi}. \qquad (4.6.4\ d)$$

The IEI also requires a modification in its equation to match its definition with other conceptual and operational dimensions of sprawl,

$$\mathrm{IEI}' = 1 - \sum_{i=1}^{n} \frac{\psi_i \left(\mathrm{E} - \mathrm{E}_i \right)}{\mathrm{E} \cdot \psi}. \qquad (4.6.4\ e)$$

The value of IEI is 0 when all of its residential development condenses in one single subarea with the entire non-residential land scattered in some or all of the rest of subareas. In contrast, the IEI will maximise its value at +1.0 when all subareas contain the same proportion of land uses as the average residential proportion.

4.6.5 The Relative Entropy Index (REI)

Different from the IEI in the sense of weighting, 1/log$N$ can be taken into the calculation of REI in order to normalise its maximum degree to +1.0. The formula of REI is

$$\mathrm{REI} = \frac{1}{\log N} \cdot \sum_{i=1}^{n} \left(\frac{\phi_i}{\sum_{i=1}^{n} \phi_i} \cdot \log \frac{\sum_{i=1}^{n} \phi_i}{\phi_i} \right). \qquad (4.6.5)$$

Among the five proposed indicators of 'evenness', REI is the only equation that does not need any adjustment. The degree of REI reaches its maximum value at +1.0 when all subareas have the same proportion of land uses as the average residential proportion.

On the contrary, the REI will minimise its value at 0 when all of its residential land of the development condenses into one single subarea, no matter how non-residential land disperses into other subareas. When there is no non-residential land in the city, the value of IEI is significantly affected. For example, a city that has no non-residential land and all of its residential land condensed in one sub-unit, IEI conversely gives the value of 0 while REI is not affected by this situation. It can be said that REI is a more stable indicator than IEI.

It should be noticed that the ratio of a subarea's residential proportion to the sum of every subarea's residential proportion can be applied to the calculation of both IEI and REI due to the fact that the aforementioned ratio absolutely meshes with the concept of probability which is one of the main concepts used in defining entropy.

4.7 CONCENTRATION

Before investigating each concentration indicator, the distinction between the concept of density and concentration will be discussed first. Imagine first that city 'A' and 'B' have the same size of area, with their areas of residential land being 50 and 100 square metres, respectively. It is obvious that the density of the city 'A' is half that of city 'B'. However, all of the residential land is spread throughout city 'B' while all of residential land is located in one subarea in city 'A'. So the concentration of city 'A' is higher even though the density is lower. Theoretically, it can be said that the entire area is taken into consideration when attempting to identify the density of a city but comparative analysis of subareas to the whole should be the main issue in judging the degree to which land uses and development are concentrated in the city. In addition, concentration refers to the relative amount of physical space occupied by the relevant activities or land uses in the urban environment. However, there are very few indicators of spatial concentration that have been suggested in the urban research literature and here we are the first to pull these different measures based on the Delta, the Absolute Concentration Index, and the Relative Concentration Index together.

4.7.1 DELTA (DEL)

The DEL index calculates the proportion of residential land locating in areal units with above average density of residential land. It is interpreted as the share of the residential land that would have to move so as to achieve a uniform concentration of residential land use in the overall area. The formula can be written as

$$\text{DEL} = \frac{1}{2} \cdot \sum_{i=1}^{n} \left| \frac{\varepsilon_i}{\varepsilon} - \frac{\delta_i}{\delta} \right|. \tag{4.7.1}$$

The DEL index is a specific application of the more general IOD. It measures the spatial concentration of residential land use in an absolute sense. The index gives the minimum value of 0 when the ratio of residential land and developable land gives the same degree in every subarea i.e., $\varepsilon_1/\delta_1 = \varepsilon_2/\delta_2 = \varepsilon_3/\delta_3 = \ldots = \varepsilon_n/\delta_n$. A lower value of DEL means that residential land is more evenly concentrated throughout the city while a higher value means that all residential land is concentrated in a few subareas. Without regard to the distribution or the existence of non-residential land, in the extreme case of all residential land locating in a single subarea, the value of DEL will be higher and will approach +1.0 when the size of that developable land is relatively small compared to the rest of the developable land which has no residential use.

4.7.2 THE ABSOLUTE CONCENTRATION INDEX (ACO)

The ACO computes the total land that is occupied by residential land and compares this figure with the minimum and maximum possible areas that could be occupied by residential land in a given city, as shown by the following formula:

$$\text{ACO} = 1 - \left(\frac{\sum_{i=1}^{n} \frac{\varepsilon_i \delta_i}{\varepsilon} - \sum_{i=1}^{n_1} \frac{\psi_i \delta_i}{\tau_1}}{\sum_{i=n_2}^{n} \frac{\psi_i \delta_i}{\tau_2} - \sum_{i=1}^{n_1} \frac{\psi_i \delta_i}{\tau_1}} \right). \tag{4.7.2}$$

In order to find τ_1 and τ_2, n_1 refers to different positions in the ranking of areal units ordered from the smallest to largest according to the developable land size; n_1 is the rank of the tract where the cumulative developed land areas, totalling from the smallest subarea up, have reached the amount of total residential land area of the entire city, while n_2 is the rank of the tract where the cumulative developed land area, summing from the largest subarea downwards, have reached the amount of total residential land area of the entire city. The sum of developed land area from tract 1 to n_1 is τ_1 and τ_2 is the sum of developed land area from tract n_2 to n (as we show in Tables 4.5, 4.6 and 4.7).

In the numerator, the first term summarises the average concentration of residential land use through the distribution of residential land in each subarea compared to total residential land, taking the weight of the developable land in each subarea into consideration. The second term represents the scenario that all residential land occupies the land starting from the smallest subarea or the situation in which residential land is distributed under conditions of maximum spatial concentration. The first term of the denominator is the average land area that would be occupied under the condition of minimum concentration characterising the situation of all residential land locating in the largest areal units.

The index varies from 0 to +1.0, where a score of +1.0 indicates that the residential land use has achieved the maximum spatial concentration possible (all residential land is located in the smallest areal units). A score of 0 means the minimum concentration possible where the largest areal units are occupied by residential land. However, the degree of ACO is influenced by the case that has more than one subarea with the same size of developable land, due to the ambiguity in ranking n_1 and n_2 which also affects the derivation of τ_1 and τ_2.

Table 4.5: The city 'Z' with the values of ε_i, ω_i, ψ_i and δ_i of areal units Z_1 to Z_5

Areal Unit	ε_i	ω_i	ψ_i	δ_i
Z_1	6	2	8	10
Z_2	12	0	12	25
Z_3	4	8	12	20
Z_4	14	6	20	30
Z_5	6	4	10	15

Table 4.6: How to obtain the values of n_1 and τ_1

Areal Unit	δ_i	ψ_i	Summing ψ_i	ε_i
Z_1	10	8	8	6
Z_5	15	10	18	6
Z_3	20	12	30	4
Z_2 n_1	25	12	**42**	12
Z_4	30	20	62	14
			Total	**42**

Ordering from the smallest unit up

$\tau_1 = 8+10+12+12 = 42$

Summing from the smallest unit

Table 4.7: How to obtain the values of n_2 and τ_2

Areal Unit	δ_i	ψ_i	Summing ψ_i	ε_i
Z_1	10	8	62	6
Z_5	15	10	54	6
Z_3 n_2	20	12	**44**	4
Z_2	25	12	32	12
Z_4	30	20	20	14
			Total	**42**

Ordering from the smallest unit up

$\tau_2 = 20+12+12 = 44$

Summing from the largest unit

4.7.3 THE RELATIVE CONCENTRATION INDEX (RCO)

A study in segregation between minority and majority groups shows that there is a distinct difference in how both of these two groups are distributed. With regard to the distribution of residential and non-residential land uses, relative measurement in the degree of concentration is proposed in the form of a relative concentration index:

$$\text{RCO} = \frac{\sum_{i=1}^{n}\frac{\varepsilon_i\delta_i}{\varepsilon}}{\left(\sum_{i=1}^{n}\frac{\omega_i\delta_i}{\omega}\right)-1} \Bigg/ \frac{\sum_{i=1}^{n_1}\frac{\psi_i\delta_i}{\tau_1}}{\left(\sum_{i=n_2}^{n}\frac{\psi_i\delta_i}{\tau_2}\right)-1} \tag{4.7.3}$$

where n_1, n_2, τ_1 and $\tau_2$can be derived in the same way as in the case of ACO. The RCO takes the ratio of residential land use to non-residential land use concentration and compares such a ratio with the denominator which refers to the maximum ratio that would be engaged if residential land use was maximally concentrated and non-residential land use minimally concentrated. Standardising the quotient provides the minimum and maximum values of RCO which are -1.0 and +1.0, respectively. A score of zero means that both land uses are equally concentrated in the city. A score of +1.0 means that residential concentration exceeds non-residential concentration to the maximum extent possible while a score of -1.0 means the opposite.

Greater numbers of subareas that contain the same amount of developable land in any city has an effect on the values of ACO and RCO due to ambiguities in ranking n_1 and n_2 which also affect the derivation of τ_1 and τ_2. Furthermore, in the case where non-residential land is absent from the city and all of residential land agglomerates in one subarea, the value of ACO is adversely distorted from 0 to 1 but DEL is not susceptible to the aforementioned situation.

4.8 Exposure

Exposure refers to the degree of potential contact, or the possibility of interaction, between or among groups of relevant activities or land uses within geographical areas of a city. Indicators of exposure evaluate the degree to which residential and non-residential land uses are exposed to each other by virtue of sharing the same subarea. The concept of exposure focuses on the relative size of each group, between ε and ω in this study, being compared.

4.8.1 The Interaction Index (INT)

The formula for INT is

$$ {}_{\varepsilon}\mathrm{INT}_{\omega} = \sum_{i=1}^{n} \frac{\varepsilon_i}{\varepsilon} \cdot \frac{\omega_i}{\psi_i}. \qquad (4.8.1)$$

The indicator varies between 0 to 1 by computing the residential-weighted average of each geographical unit's non-residential land-use proportion. It can be interpreted as the probability that a randomly chosen residential unit shares an area with a non-residential unit. The score approaching 1.0 means a high possibility of interaction between these two land uses while a score which is near the value of 0 means the opposite.

Similar to the concept we used in measuring the IOD, the degree of INT gives a value of zero when there is absolutely no mix between residential and non-residential land uses in any subareas. However, the maximum values of INT and IOD are distinct in their meaning. Examining INT equation, a lesser amount of residential land, compared to the amount of non-residential land, tends to produce a higher probability of interactions with others. The value of INT approaches its maximum value of 1.0 when, in each subarea, the proportion of non-residential land is much more than residential land.

4.8.2 The Eta Squared Index (ETA)

The reverse measurement of INT is the Isolation Index (ISO):

$$ \mathrm{ISO} = \sum_{i=1}^{n} \frac{\varepsilon_i}{\varepsilon} \cdot \frac{\varepsilon_i}{\psi_i}. \qquad (4.8.2\ a)$$

It measures the interaction within the same group of activities using the concept of probability. Consequently, in this study, such an indicator can be written in another form which is ${}_{\varepsilon}\mathrm{INT}_{\varepsilon}$. In the two-group case, the summation of INT and ISO equals one. In general, asymmetry can be found in the INT indices and this means that ${}_{\varepsilon}\mathrm{INT}_{\omega}$ does not equal ${}_{\omega}\mathrm{INT}_{\varepsilon}$. Except when two groups of activities share the same proportion of the built-up land area will the indicators be equivalent to one another. To remove this asymmetry and to control the effect of compositional dependence, ISO is developed into Eta Squared (ETA):

$$\text{ETA} = \frac{\text{ISO} - \phi}{1 - \phi}. \qquad (4.8.2\,b)$$

Since the meanings of the minimum and maximum values of ETA are opposite to those of INT, we need to adjust the ETA equation as:

$$\text{ETA}' = 1 - \frac{\text{ISO} - \phi}{1 - \phi}, \qquad (4.8.2\,c)$$

and this is required when comparing these indices together. When residential and non-residential land use does not exist in any of the same subareas, ETA′ generates its minimum value of zero. In the case of maximum value of ETA′, this measures the degree of exposure in both ways with respect to how much residential land use is exposed to non-residential land use (ε to ω) and vice versa (ω to ε). Regardless of the amount of land, the co-existence of residential and non-residential land uses in the same subareal unit results in maximising the value of ETA′. This implies that the index of ETA′ does not depend on an assumption that lesser amounts of one specific land use, relative to others, have the propensity of drawing higher interactions between them.

All of twenty-three of the potential indicators we have introduced are reviewed in relation to the eight operational dimensions and three conceptual dimensions of sprawl that we have present in this chapter. These are summarised in Table 4.8. It is clear that except for the dimension of average density, there is more than one potential indicator that can be used to estimate one single operational dimension; consequently, the next important step is to select the most suitable indicator for measuring each operational dimension of sprawl. However, prior to that and other analysis, we need to discuss the units of analysis, the main data sources used in the analysis, and the various case studies that we have defined. These will be discussed next in Chapter 5.

Table 4.8: Summary of the reviewed potential indicators of sprawl

Conceptual Dimension of Sprawl	Operational Dimension of Sprawl	Potential Indicator	Ranges
1) Density	1.1) Average density	1.1.1) Average Land-use Density (ALD)	0 to +1
	1.2) Density Gradient	1.2.1) Density Gradient: Inverse power function (DGI)	-α to +α
		1.2.2) Density Gradient: Negative exponential function (DGN)	-α to +α
2) Configuration	2.1) Complexity	2.1.1) Perimeter-Area Ratio (PAR)	-α to +α
		2.1.2) Fractal Dimension: Slit-island method (FDS)	+1 to +2
		2.1.3) Fractal Dimension: Box method (FDB)	+1 to +2
	2.2) Clustering	2.2.1) Moran's I Coefficient(MORAN)	-1 to +1
		2.2.2) Geary Coefficient (GC′)	-1 to +1
		2.2.3) Index of Absolute Clustering (ACL)	0 to +1
		2.2.4) Index of Spatial Proximity (ISP)	-α to +α
		2.2.5) Index of Relative Clustering (RCL)	-α to +α
	2.3) Centralisation	2.3.1) Absolute Centralisation Index (ACE)	-1 to +1
		2.3.2) Relative Centralisation Index (RCE)	-1 to +1
3) Composition	3.1) Evenness	3.1.1) Index of Dissimilarity (IOD′)	0 to +1
		3.1.2) Gini Coefficient (GINI′)	0 to +1
		3.1.3) Atkinson Index (AI)	0 to +1
		3.1.4) Information Entropy Index (IEI′)	0 to +1
		3.1.5) Relative Entropy Index (REI)	0 to +1
	3.2) Concentration	3.2.1) Delta (DEL)	0 to +1
		3.2.2) Absolute Concentration Index (ACO)	0 to +1
		3.2.3) Relative Concentration Index (RCO)	-1 to +1
	3.3) Exposure	3.3.1) Interaction Index (INT)	0 to +1
		3.3.2) Eta Squared Index (ETA′)	0 to +1

CHAPTER 5: RESEARCH FRAMEWORK AND CONTEXT SETTING

This chapter begins with a further elaboration of the research framework that we have hinted at previously and which we now show in Figure 5.1. This constructs the foundation for Chapters 5 and 6 of this thesis in relation to the sequence of steps involved in modelling sprawl.

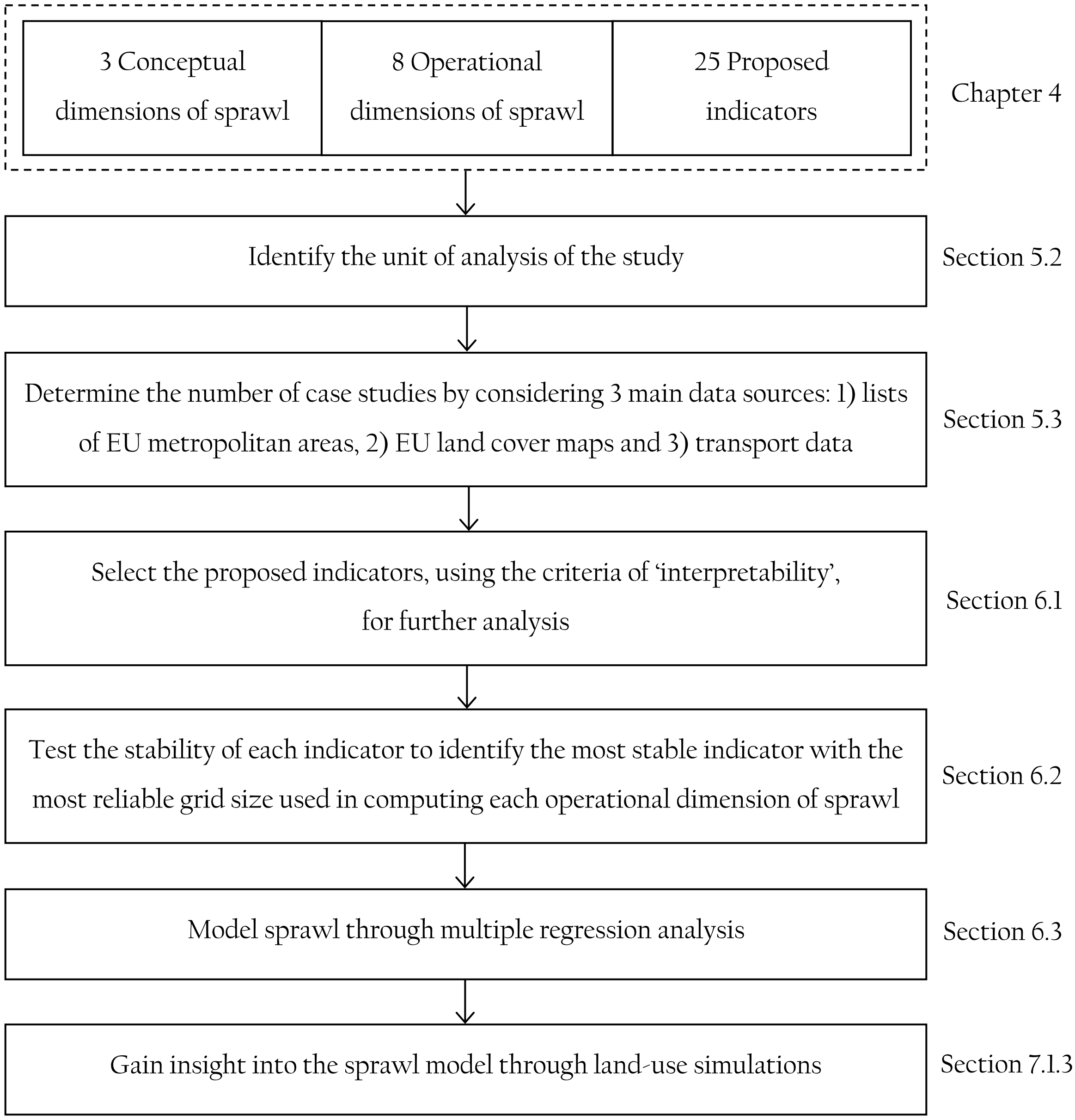


Figure 5.1: The research framework in modelling sprawl

5.1 Research Methodology

It is worth re-stating that according to the main hypothesis of this study in modelling sprawl, our major independent variables that we use to determine and explain sprawl are based on those quantitative characteristics of urban sprawl that we have already reviewed while the dependent variable is the distance travelled by private motorised vehicles. Identifying the unit of analysis for this study must also correspond to the unit used in collecting secondary data pertaining to distance travelled which is across the entire metropolitan area. To give this the correct context, we compare our analysis with work by the ESPON project 1.4.3 of European Spatial Planning Observation Network and the Organisation for Economic Cooperation and Development (OECD) which we scrutinise in Section 5.2.

From our review of the twenty-three indicators of sprawl according to our eight operational dimensions and three conceptual dimensions, land cover maps that are available for various European metropolitan areas will be used as the basis for calculating twenty-five proposed indicators, which increase from the original 23 because three different values of μ based on 0.1, 0.5 and 0.9 will be applied in the calculation of AI (which we call AI.1, AI.5 and AI.9). The land cover maps will be organised to gain two main pieces of quantitative information i.e., area and distance. More details about how we have extracted the information about area from the land cover map will be described in Section 5.3, and the information about distance measurements we will present at the beginning of Chapter 6.

When all of the twenty-five indicators have been calculated which we do through programs written with MATLAB© scripting, the conditions used in sieving the sprawl's quantitative characteristics, mentioned earlier in Section 2.5, will be applied. We will also introduce the stability test in Section 6.3, in order to select the most stable indicator for estimating each operational dimension of sprawl. Then selected indicators for each of the EU metropolitan areas that have appropriate data on distance travelled made by motorised private vehicles, will use a multiple regression framework as a basis for creating the sprawl model.

In summary, there are three main steps that this study needs to prepare before we launch into modelling urban sprawl. First, we need to determine the unit of analysis. Second, in obtaining the case studies that can be used to model sprawl, it is indispensable that we cross-check the case studies with respect to the lists of EU metropolitan areas, transport datasets and the availability of land cover maps (Section 5.3). Third, among indicators used in calculating the same operational dimensions of sprawl, we need to identify the most suitable one for each dimension in terms of its level of relative stability. When these three main steps have been fulfilled, we will be in a position to model sprawl.

5.2 METROPOLITAN AREAS AS THE UNIT OF ANALYSIS

The secondary transport data have been gathered with co-operation between the International Association of Public Transport (UITP) and the Institute for Sustainability and Technology Policy (ISTP). The definitions that UITP and ISTP use in defining the cities in their surveys will be used as the basis for defining the unit of analysis of this study.

In collecting transport data for the year 1995, the UITP and ISTP indicate that they define their metropolitan areas based on the administrative areas that best correspond to the functional area, in defining each city (The International Association of Public Transport (UITP) & the Institute for Sustainability and Technology Policy (ISTP, 1995)). Although most of the data do not accurately match these ideal areas, a consistent of such terms is still necessary.

Concerning the issues in identifying the areas encompassed in each metropolitan area in Europe, the two different sources we use are from the ESPON project 1.4.3 of European Spatial Planning Observation Network and the Organisation for Economic

Cooperation and Development (OECD). First, the ESPON project takes the perspective that apart from their morphological character and population density, cities also reflect functional dimensions in the form of employment cores, surrounded by a massive labour pool. They approach the city as being basically organised around a dense node of population. They start by adding all the municipalities at NUTS-5 level which have more than 650 people per km^2 or have a clear concentrated core with more than 200,000 inhabitants. These considerations lead to their definition of Morphological Urban Areas (MUAs). NUTS stands for Nomenclature of Units for Territorial Statistics and it is a geocode standard for referencing the subdivisions of countries for statistical purposes regulated by the European Union, thus covering the member states of the EU in detail but built from local administrative units, such as wards in the UK. There are five levels of NUTS, NUTS-1 (the largest subdivision) to NUTS-5 (the smallest subdivision). Then, the aspects of administrative functions, decision functions, transport functions, knowledge functions and tourism functions of all of the Functional Urban Areas (FUAs) are examined. Through this approach, FUAs are defined with respect to incorporating the so-called labour basins of the MUAs (based loosely on travel to work areas or commuting thresholds) In other words, ESPON suggests that the characterisation of the MUAs should be incorporated in the characterisation of the FUAs in defining a standard set of metropolitan areas across Europe (European Spatial Planning and Observation Network 2007).

Second, the unit of analysis that the OECD uses in defining metro-regions is based on territorial levels (TL), one of which is territorial level 3 (TL3). These regions refer to:

- *Upper Tier Authorities* in the United Kingdom
- *Provinces* in Belgium, Italy, the Netherlands, Spain, and Sweden.
- *Departments* in France.
- *Development Regions* in Greece.
- *Gruppen von Politischen Bezirken* in Austria.
- *Kraje* in the Czech Republic.
- *Amter* in Denmark.

- *Maakunnat* in Finland.
- *Regierungsbezirke* in Germany.
- *Megyek* in Hungary.
- *Lan* in Sweden.

Their methodology takes five criteria to support a specific collection of units of analysis that conform to a single urban space. These factors can be broadly classified as based on administrative or legal boundaries, labour markets, business linkages, services centres and housing markets. At a first step, a criterion of less than 15% of the population inhabiting rural areas with a population density under 150 inhabitants/m^2 are used to screen out the Predominantly Urban areas (PU) with more than 1,000,000 inhabitants. Then, commuting rate flows for each of the PU are used to calculate a Net Commuting Rate (NCR) for a set of PU areas. If the NCR is above 10 percent, one intermediate PU area at a time is added until the rate reaches the metro-region level. Finally, an area is considered to be such a metro-region if its population is above 1.5 million inhabitants. The OECD also applies this methodology and various mathematical functions in estimating the values of indicators such as data on gross domestic product in situations of missing data or those cases in which data is only available for an area considerably larger than the unit of analysis (Organisation for Economic Co-operation and Development 2006).

In identifying these metropolitan areas, both the approaches of the OECD and ESPON integrate viewpoints about population agglomeration and administrative boundaries, and also reflect several intangible dimensions of urban activities, especially commuting volumes. It can be considered that both sources reasonably fit with the definition of metropolitan areas given by the UITP and ISTP in their collection of transportation data. However, the metropolises in ESPON's project are presented only by their names and their numbers of population; moreover, polynucleated-FUAs are their main concentration of research where some of them are spatially disconnected. In contrast, the list of metropolitan areas of OECD is useful to this study because subunits of their administrative boundaries included in each metro-region are also provided. Thus, we have decided to use the list of 38 European metropolises of the OECD (see Appendix A) as the basis of our case studies which we use to progress the analysis in this study.

5.3 DATA AND CASE STUDIES

There are three main dataset for the European countries used here include: 1) lists of metropolitan areas (Appendix A), 2) land cover maps and 3) the 'distance travelled' dataset. Since the numbers of the units of observation areas that each dataset provides do not perfectly match, a cross-analysis of these datasets acknowledges that there are differences in the number of case studies that can be applied in the tests of stability and the models that are used to explain sprawl as we show in Figure 5.2.

While the relevant administrative boundary maps have also been downloaded from the VDS technologies website, this study obtains land cover maps of countries that are members of the European Union for the year 2000. These maps are at 250-metre resolution, taken from the CORINE Land Cover (CLC) data set for 2000 which is part of the European Commission programme for COoRdination of INformation on the Environment (CORINE) developed by the European Environment Agency (EEA). The CLC dataset maps the landscape based on two main properties: 1) its natural bio-geographical properties (e.g. natural grassland) and 2) its anthropogenic uses (e.g. pastures, arable land, plantations). This satellite-based mapping approach involves on-the-ground monitoring by showing the wider land use context for individual sites. It allows specific land cover features such as a forest or a landfill site to be viewed in relation to their surrounding environment and their interactions with it. CLC's spatial parcels represent fundamental landscape systems that can be interpreted as land use systems; furthermore, CLC data is mapped at a spatial scale of 25 hectares all across Europe which allows this study to accomplish the analysis at regional levels.

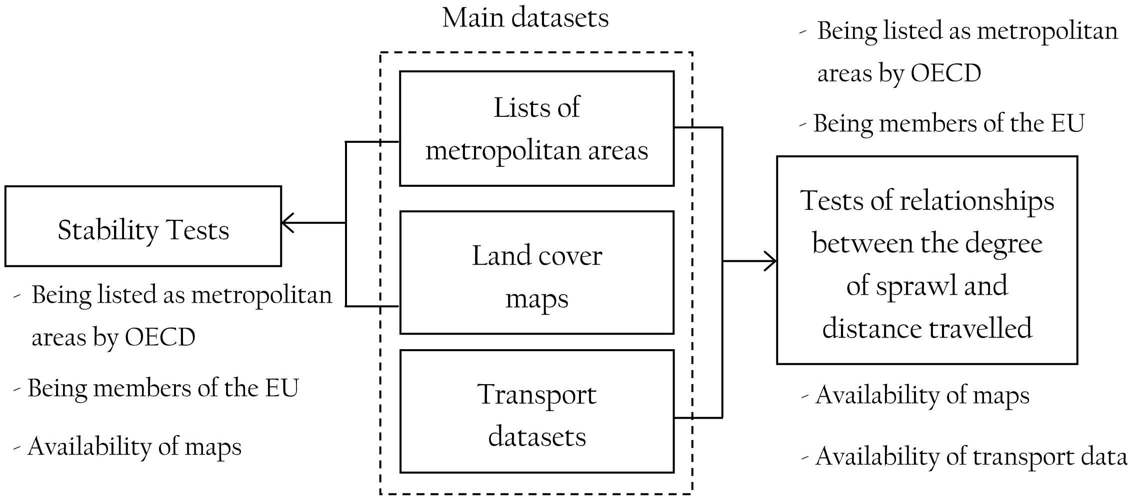


Figure 5.2: Cross-examination for obtaining the case studies

Amongst 38 European metropolitan areas, there are 8 metropolises that are excluded from the stability tests. Land cover maps for Oslo, Norway, Zurich, Switzerland, Ankara, Istanbul and Izmir, Turkey are not available from the CORINE land cover 2000 because these countries are not members of the EU. Moreover, there is ambiguity in defining the administrative boundaries of units contained in the metropolitan areas including Bayerischer Untermain and Osthessen in Frankfurt, Bremerhaven, Hamburg-Umland-Sud, Luneburg, Schleswig-Holstein Sud-West, and Sudheide in Hamburg, and Krakowsko-Tarnovski in Cracow. Lists of 30 metropolitan areas that can be analysed in the stability tests are shown in Table 5.1.

As mentioned in Section 3.2 and in relation to the dimensions of ‘density’ and ‘configuration’, residential land use is highlighted as it is one of the main activities that define a city. However, the distribution of residential land use relative to non-residential use is another focus of this study in accordance with the concept of composition. Consequently, from the embedded 44 classes of the CORINE land cover data, these were classified into three main categories: 1) residential land use, 2) non-residential land use and 3) developable land (see Appendix B). Developed land areas or urbanised land can be obtained when combining the first two land-uses areas together. Moreover, instead of using the total amount of land in each city, we consider only developable land, the developed land which combines with land that has potential to be developed, thus reflecting the potential size of the city.

From the criteria of *objective* and *interpretability* used in deriving the sprawl indicators discussed in Section 2.5, these two conditions imply that the sprawl index must count on data that are quantifiable and must be collected without bias. Using land cover maps as the basis for quantifying the degree of sprawl reasonably meets such criteria since numerical data in the form of areas can be extracted from the polygons defining the four main land-use categories presented in each map.

Table 5.1: List of 30 metropolitan areas that are analysed in the stability tests

Country	Metropolitan Area	Country	Metropolitan Area
Austria	1) Vienna	Italy	16) Milan
Belgium	2) Brussels		17) Naples
Czech Republic	3) Prague		18) Rome
Denmark	4) Copenhagen		19) Turin
Finland	5) Helsinki	Netherlands	20) Randstad
France	6) Lille	Poland	21) Warsaw
	7) Lyon	Portugal	22) Lisbon
	8) Paris	Spain	23) Barcelona
Germany	9) Berlin		24) Madrid
	10) Munich		25) Valencia
	11) Rhein-Ruhr	Sweden	26) Stockholm
	12) Stuttgart	United	27) Birmingham
Greece	13) Athens	Kingdom	28) Leeds
Hungary	14) Budapest		29) London
Ireland	15) Dublin		30) Manchester

Concerning the dataset on transportation, out of 100 world cities, data on 40 European cities are collected through surveys from the UITP and ISTP. Data on average distance travelled per capita (kilometres/capita) can be derived when multiplying the daily-trip-per-capita data (Appendix C) with average-trip-distance data (Appendix D). The average number of daily trips is the average one-way trips per day within the metropolitan area, and as far as possible, only trips with origins and destinations within the metropolitan area are counted. The average length of a trip is the average kerb-to-kerb length of all trips made within metropolitan area (The International Association of Public Transport (UITP) & Institute for Sustainability and Technology Policy (ISTP) 1995).

Table 5.2 : Lists of the European metropolitan areas with transport data based on daily average distance travelled per capita made by private modes

Country	**Metropolitan area**	**Daily average distance travelled (km/capita) made by private modes**
Austria	Vienna	13.804
Belgium	Brussels	15.792
Denmark	Copenhagen	23.989
Finland	Helsinki	15.800
France	Lille	22.145
	Lyon	19.503
	Paris	14.125
Germany	Berlin	12.015
	Munich	16.200
	Ruhr	21.608
	Stuttgart	19.710
Greece	Athens	15.367
Hungary	Budapest	8.806
Italy	Milan	13.984
	Rome	20.196
	Turin	13.266
Poland	Warsaw	9.520
Spain	Barcelona	9.167
	Madrid	13.452
Sweden	Stockholm	24.123
United Kingdom	London	15.594
	Manchester	9.890
Czech Republic	Prague	12.236

The entire city names listed in Table 5.2 are based on the inventory of 38 European metropolises defined by the OECD in Table 5.1 and land cover maps of these cities are also available. Therefore from this data, we are able to select twenty-three case studies which will be used in the subsequent multiple regression analysis which is at the basis of modelling the degree of urban sprawl.

CHAPTER 6: MODELLING SPRAWL

The contents of this chapter firstly cover the area of identifying the most suitable indicators, among a total of twenty-five potential indicators, in relation to the eight operational dimensions and three conceptual dimensions of sprawl which we will outline in Sections 6.1 and 6.2. These suitable indicators will be used as the basis for modelling urban sprawl for the twenty-three European metropolitan areas which we chose as the case studies and which will be elaborated in Section 6.3.

The first task lies in the calculation of the twenty-five reviewed indicators for the thirty European metropolitan areas. Data embedded in the CORINE land cover maps can be imported into ArcMap10© to extract necessary numerical information with respect to the amount of land area from the polygons associated with different land uses that we detailed in Section 5.3. Then most of the indicators will be specified and computed after the land cover maps have been tessellated into grid square coverages which we do in Section 6.2. Physically merging contiguous residential polygons is the only map adjustment required in order to calculate these dimensions of configuration where we apply the statistical measures such as ALD, PAR, FDS, MORAN and GC′. The FDB index however requires the conversion of the physical joins of the adjacent residential polygon map to black-and-white images so that we might calculate the value of FDB through FracLac, a plugin for ImageJ software. Land cover maps of the 30 EU metropolitan areas are displayed in Appendix E.

The other numerical information required from the land cover maps is the information pertaining to distance. This study locates the centre of each metropolitan area and of each subarea by weighting the area of residential land situated within their boundaries. Additionally, as shown in Figure 6.1, there are three types of centre-to-centre distances employed in this study: 1) distance from polygon centroid to polygon centroid which is used in the case of the MORAN statistic (Section 4.4.1), and GC′ (Section 4.4.2); 2) distance from each subarea's centroid to centroid, which is applied for the ACL

(Section 4.4.3), ISP (Section 4.4.4) and RCL (Section 4.4.5) statistics; and 3) distance from subarea centroid to metropolitan area centroid, which is used to analyse the value of the ACE (Section 4.5.1) and RCE statistics (Section 4.5.2). Furthermore, in computing the indicators of 'clustering', the negative exponential of the distance between two centres, $\exp(-d_{ij})$, is adopted to define the spatial weight (W_{ij}). The distance unit of a 'meter' is scaled to 'meters/10^6' since when d_{ij} gets larger, the value of $\exp(-d_{ij})$ approaches zero. This effectively introduced a constant scaling to more appropriate units.

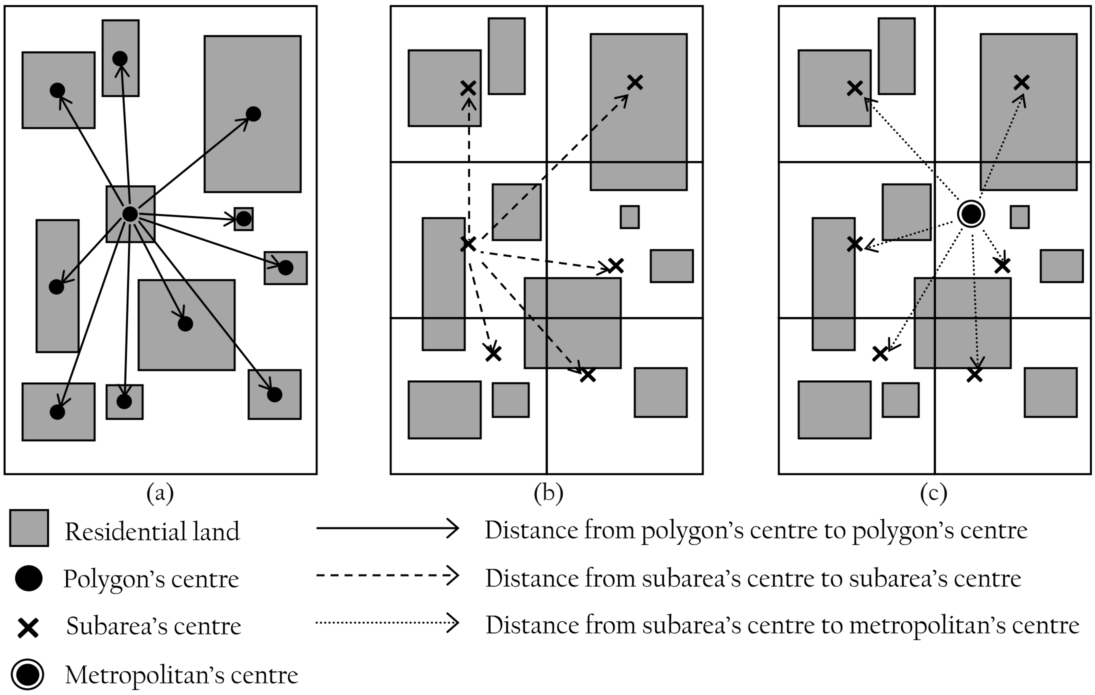


Figure 6.1: Distance from polygon centre to polygon centre (a); distance from subarea centre to subarea centre (b); and distance from subarea centre to metropolitan area's centre (c)

6.1 Conditions for Indicator Selection

It can be clearly seen in Table 4.8 that, except for the case of the operational dimension of average density, there is more than one indicator that can be used to estimate one single operational dimension of sprawl. Consequently, identification of the most suitable indicator for each operational dimension of sprawl is required along with a set of conditions; we will in fact apply four conditions in testing each indicator: 1) validation of ranges (C_1), 2) level of stability (C_2), 3) scale-dependence in real-world spatial phenomena (C_3), and 4) relative simplicity in equation structure (C_4), which we present in Figure 6.2.

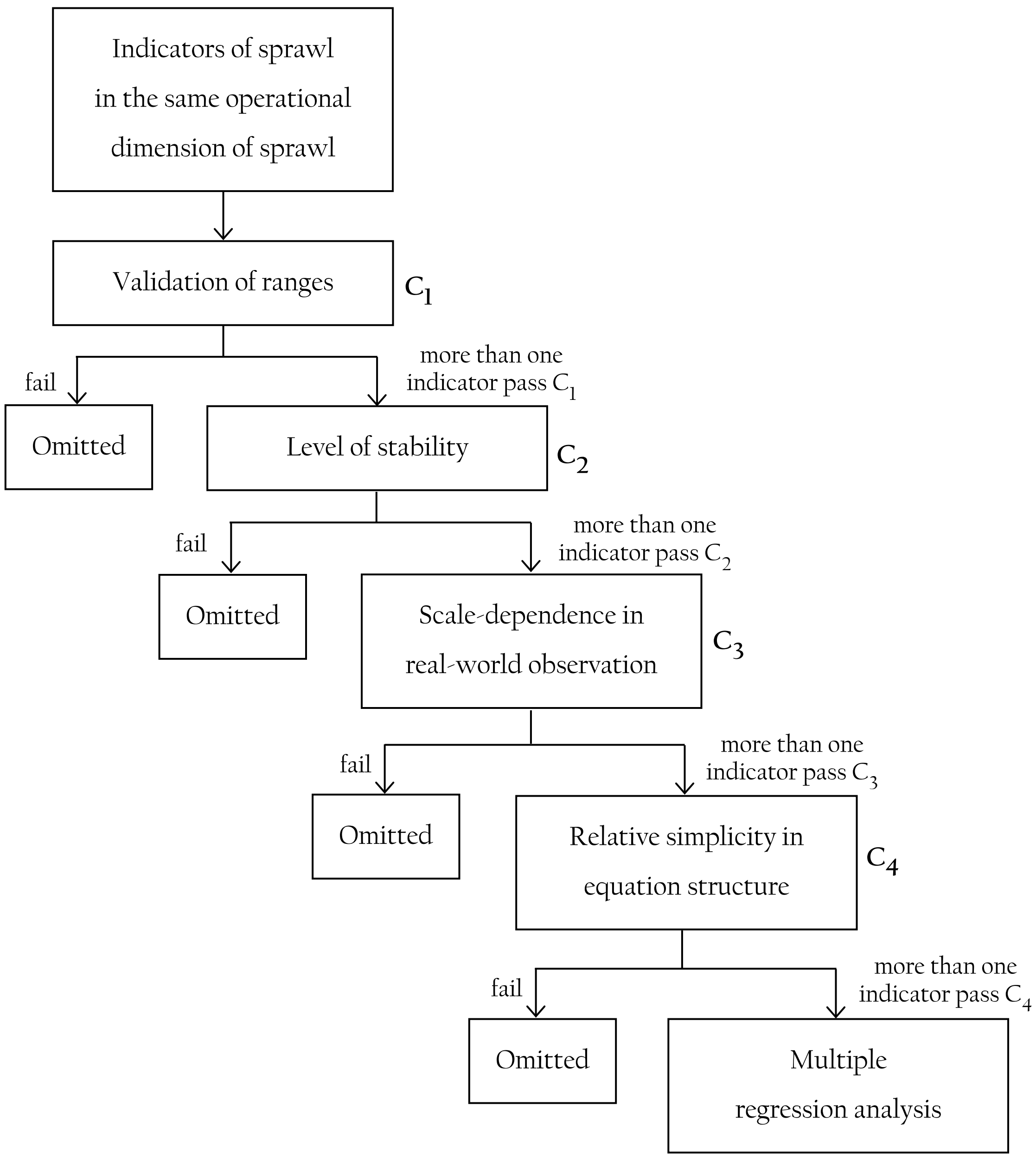


Figure 6.2: Four conditions used in searching for the suitable indicator for each operational dimension of sprawl

At any point when there is only one indicator left, additional conditions are not required. On the contrary, if after all four conditions have been applied and there is still more than one indicator left, these will be used directly in modelling the degree of sprawl using multiple regression analysis.

It is worth mentioning that the first condition works well with the criteria of *interpretability* mentioned in Section 2.5. In order for such interpretations to be meaningful, the indicator must fall within its theoretical range to meet the first condition; the FDS, ACL (equation (4.4.3)), ACO (equation (4.7.2)) and RCO (equation (4.7.3)) statistics fail to satisfy this condition, so they will be removed from further analysis in modelling sprawl (Appendix F).

The third and fourth conditions will be applied after the tests of stability have been developed which will be separately described in Section 6.2 since these contain many more details than the other conditions.

6.2 THE STABILITY TEST

In quantifying the phenomenon of urban sprawl, there are many different spatial aggregations to work with and stable indicators are necessitated in this regard. This study proposes the stability test as the second condition applied in identifying the most suitable indicators for calculating each operational dimension of sprawl. In this sense, the stability test is with respect to how stable the results of the regression are when the spatial aggregation of units is varied. We are searching of course for stability with respect to aggregation.

Displayed in Figure 6.3(b), the nature of this analysis of an indicator's stability is based on the comparison of specific spatial properties in two ways: 1) comparison among subareas (subarea 1 versus 2 until n, subarea 2 versus 3 until n,..., subarea n-1 versus n) and 2) comparison between a subarea and the entire metropolitan area (subarea 1 versus the metropolitan area,..., subarea n versus the metropolitan area) (Boontore 2011).

Areas extracted from the polygons of four main land uses (see Appendix B) are used as inputs to the calculation for each indicator through MATLAB© scripting. Two types of comparison for the stability test mentioned earlier can be fulfilled by superimposing the land-use map as a grid square tessellation on the urban landscape. Five different grid sizes are applied in these calculations, specifically: 1x1 km^2, 2x2 km^2, 3x3 km^2, 4x4 km^2 and 5x5 km^2 which we show in Figure 6.4. The bottom-left corner of the map is used as the initial position for grid tessellation (see Figure 6.3(a)). In order to eliminate the edge effect, non-built-up areas covered by the overlaid mosaic pattern are not brought into the estimation of each indicator (see Figure 6.1(b)).

The structure of the equations for ALD and PAR statistics do not allow us to test for their level of stability. In the case of FDB, different box sizes are placed upon the land cover map before the average FDB is calculated. Thus, FDB is considered as a stable indicator, though the structure of the equation is not exposed to a test for stability. The ALD, PAR and FDB statistics will be input to the model of sprawl through the multiple regression analysis (see Appendix G). In summary, there are sixteen indicators that are tested for their level of stability (see Appendix H).

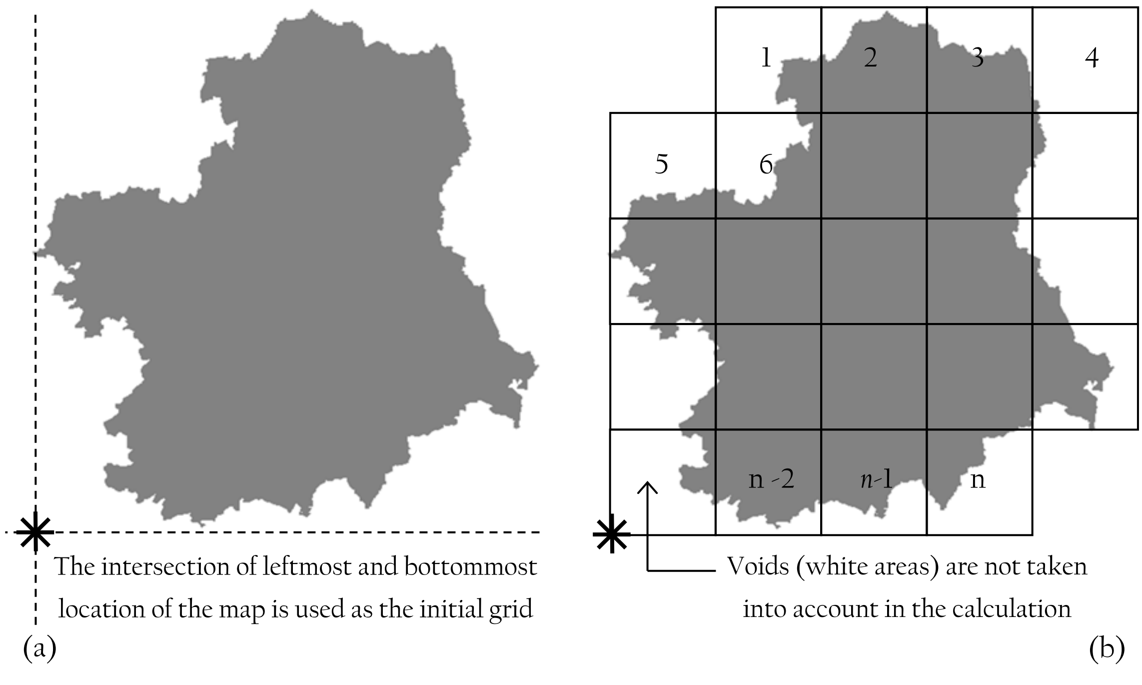


Figure 6.3: The initial grid position (a); the nature of the stability test (b)

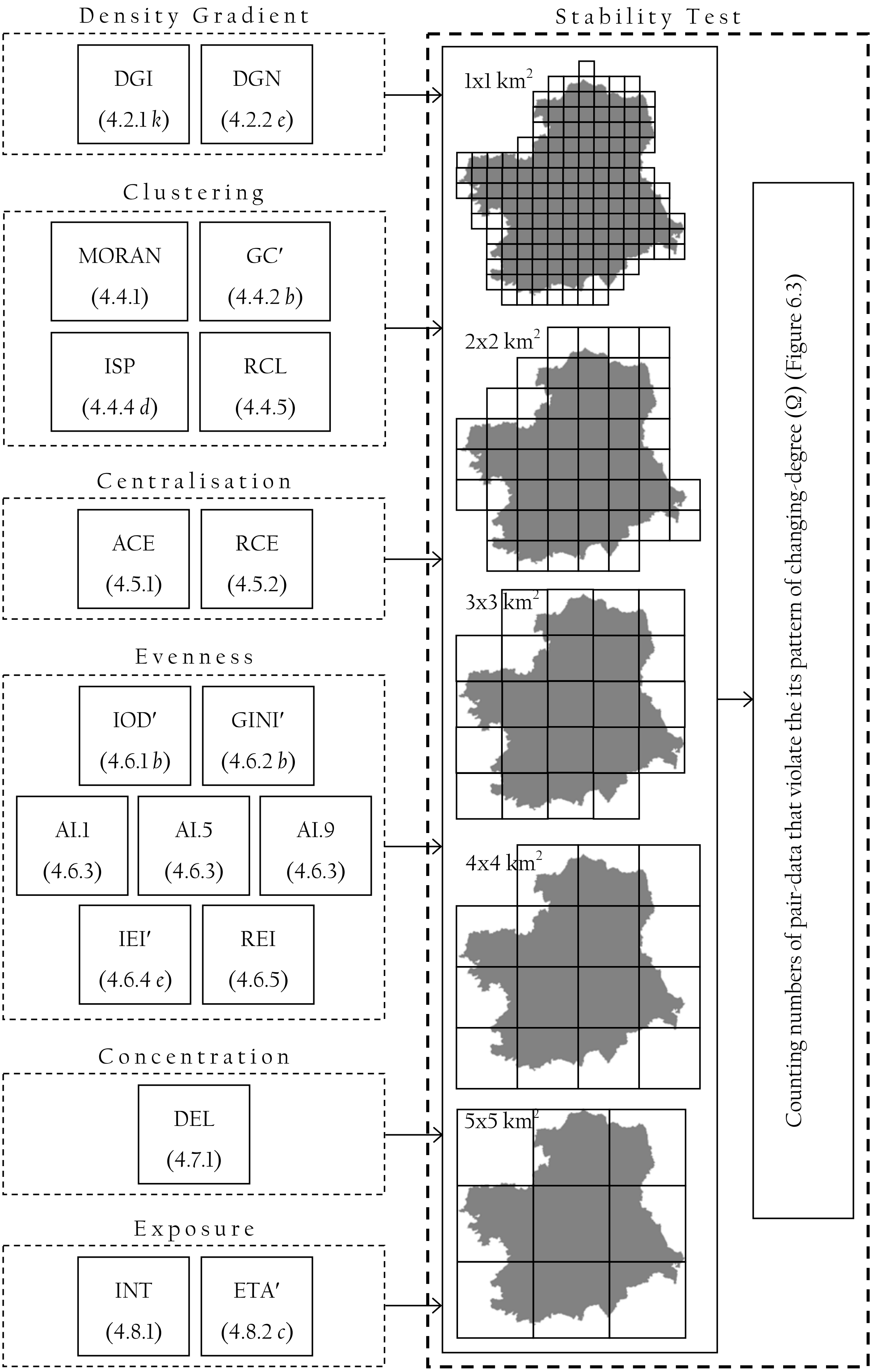


Figure 6.4: Conceptual framework for the stability test

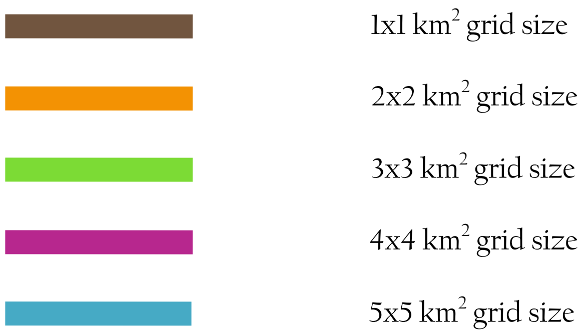


Figure 6.5: Legends applied to five grid sizes

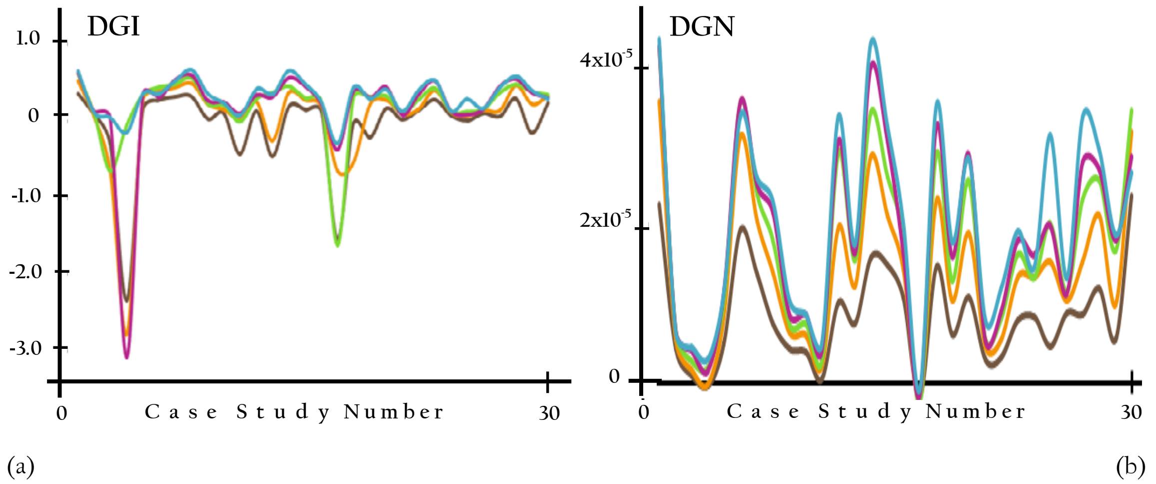


Figure 6.6: Stability plots of DGI (a) and DGN (b)

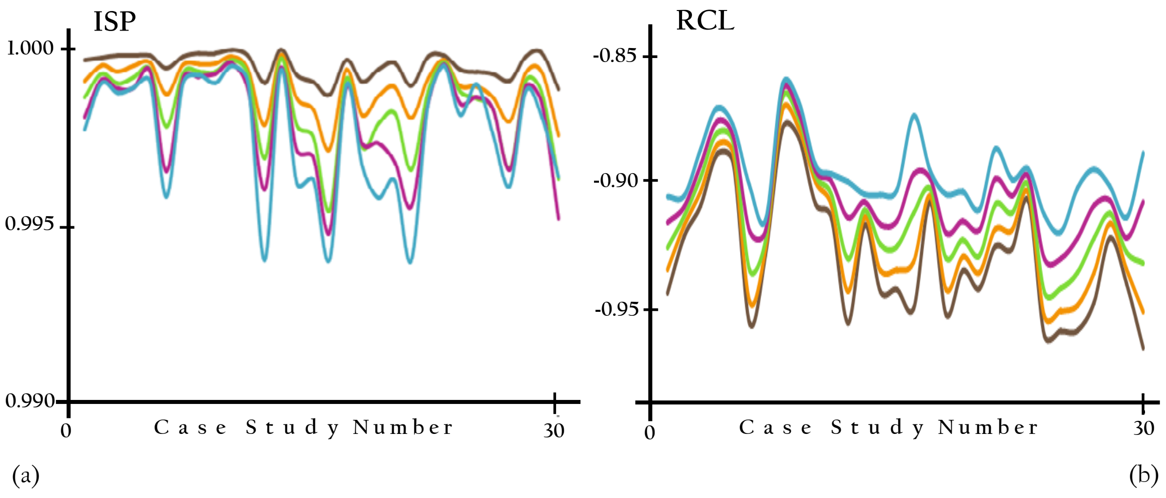


Figure 6.7: Stability plots of ISP (a) and RCL (b)

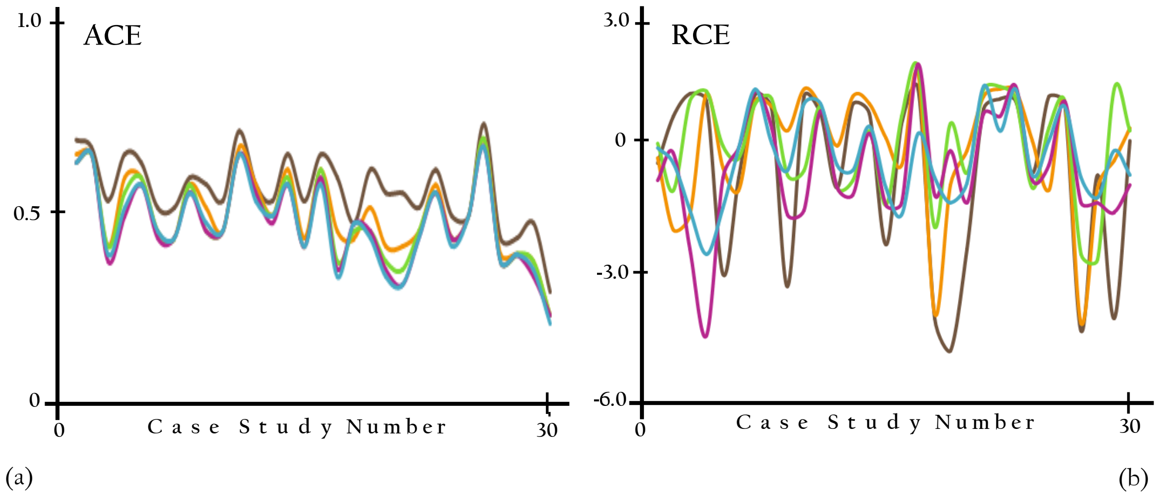


Figure 6.8: Stability plots of ACE (a) and RCE (b)

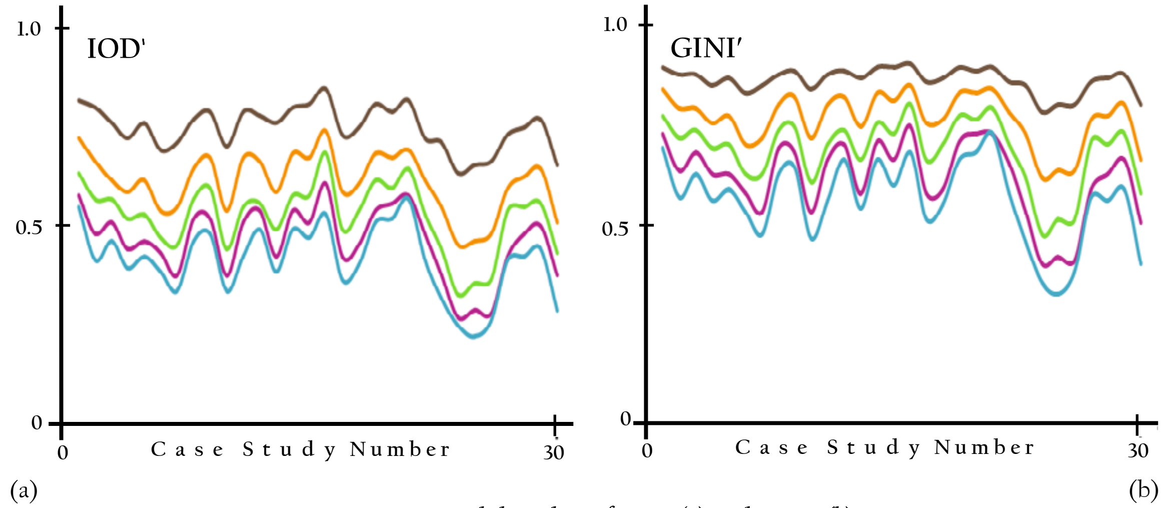


Figure 6.9: Stability plots of IOD′(a) and GINI′(b)

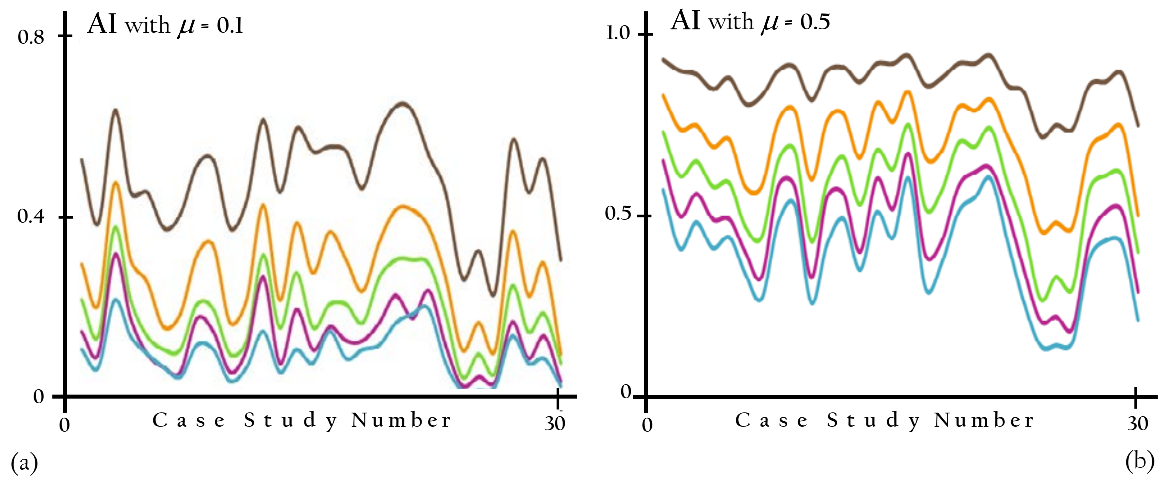


Figure 6.10: Stability plots of AI with $\mu = 0.1$ (a) and AI with the $\mu = 0.5$ (b)

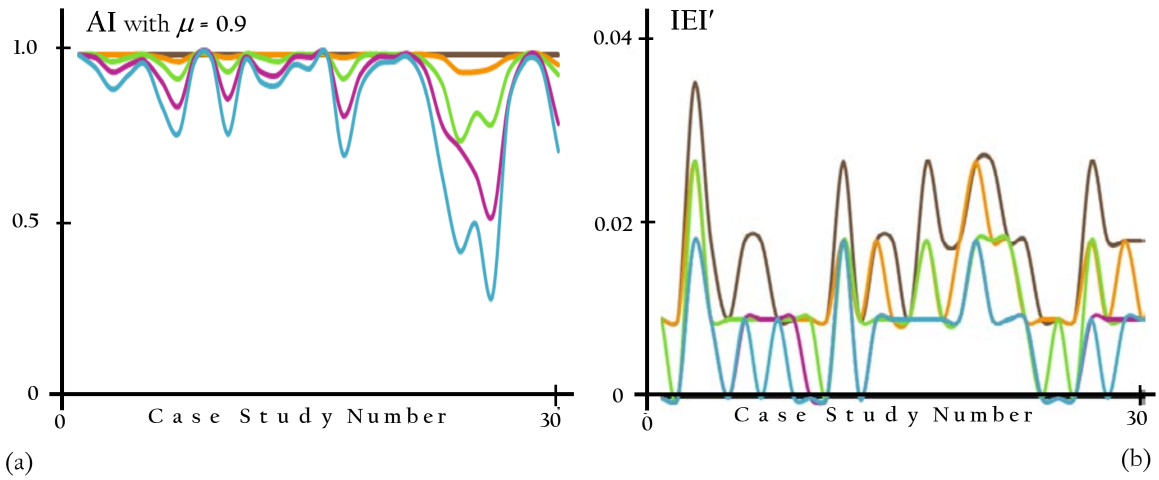


Figure 6.11: Stability plots of AI with μ = 0.9 (a) and IEI′ (b)

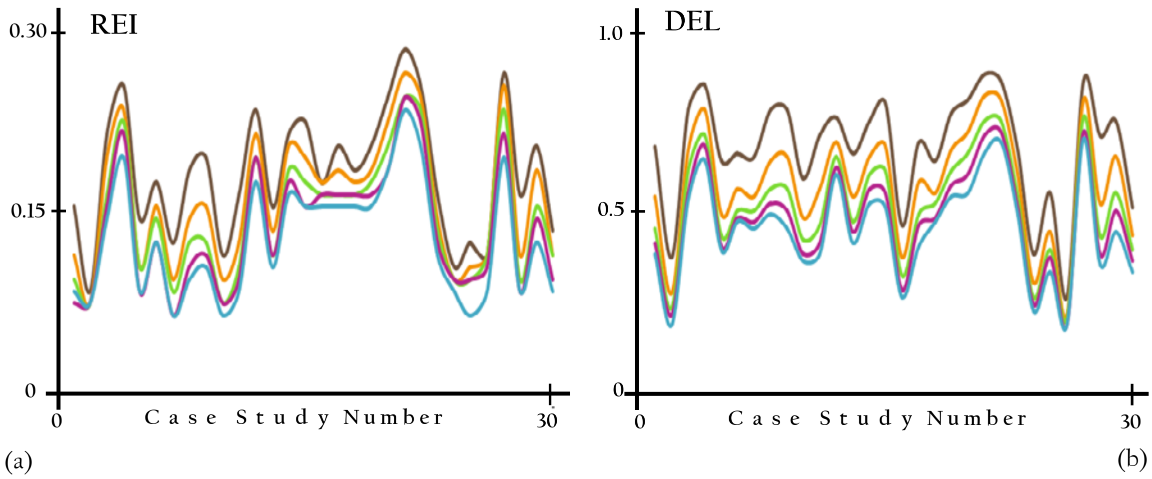


Figure 6.12: Stability plots of REI (a) and DEL (b)

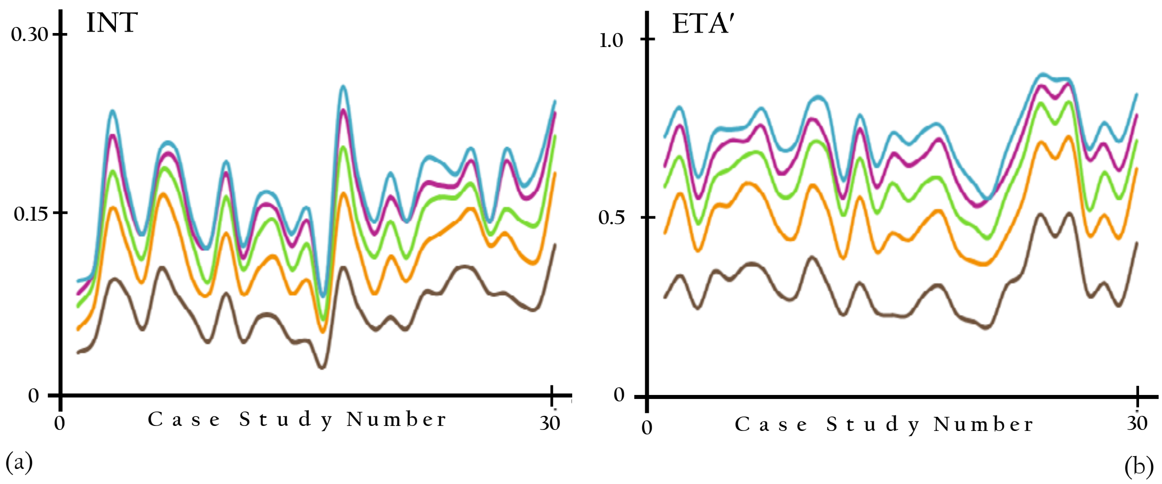


Figure 6.13: Stability plots of INT (a) and ETA′ (b)

The values for the sixteen indicators calculated by applying five different grid sizes are plotted on the same graphs as we show in Figures 6.6 to 6.13. The value of the calculated indicator is plotted on the y-axis, while the x-axis represents each individual metropolitan area.

According to one important characteristic of real-world phenomena they are scale-dependent, meaning that their properties and characteristics are different when they are observed at different scales (Lam & Cola 1993). Calculating any of these indicators at different grid sizes should affect the values of the calculated indicators. Despite the change to a smaller or bigger grid size, then stability in the direction of changing values of the indicators is expected to get smaller or larger in the same way and then such an indicator could be regarded as stable. For instance, the value of the ISP for 'city A' gets larger when changing from the grid size of 1x1 km^2 to 2x2 km^2; consequently, a higher degree of ISP is also anticipated when applying grid sizes that are larger than 2x2 m^2 in estimating the degree of ISP for that 'city A'.

Each of the case study maps will be tessellated at five different grid sizes in order to calculate a specific indicator; consequently, one single case study provides five values. Sorting these five values in each case study in ascending or descending order according to the grid sizes applied to the analysis, allows 10 comparative pairs of data which can be used to judge the level of stability for each indicator. Additionally, there are 150 values in one dataset from which a pattern for the entire dataset can be drawn. In each case study, the direction of the changing-values of all possible pairs of the calculated value of an indicator will be verified against the pattern of changing-values for its entire dataset. Numbers of pair-data violating the pattern of changing-values of the entire dataset (Ω) will be counted and their summation will be compared to other indicators in the same operational dimension of sprawl. Lesser pair-data that disagrees with the changing-value pattern of its entire dataset implies more relative stability for such an indicator. Figure 6.14 shows how to count for Ω using the values of ACL for Helsinki as an example.

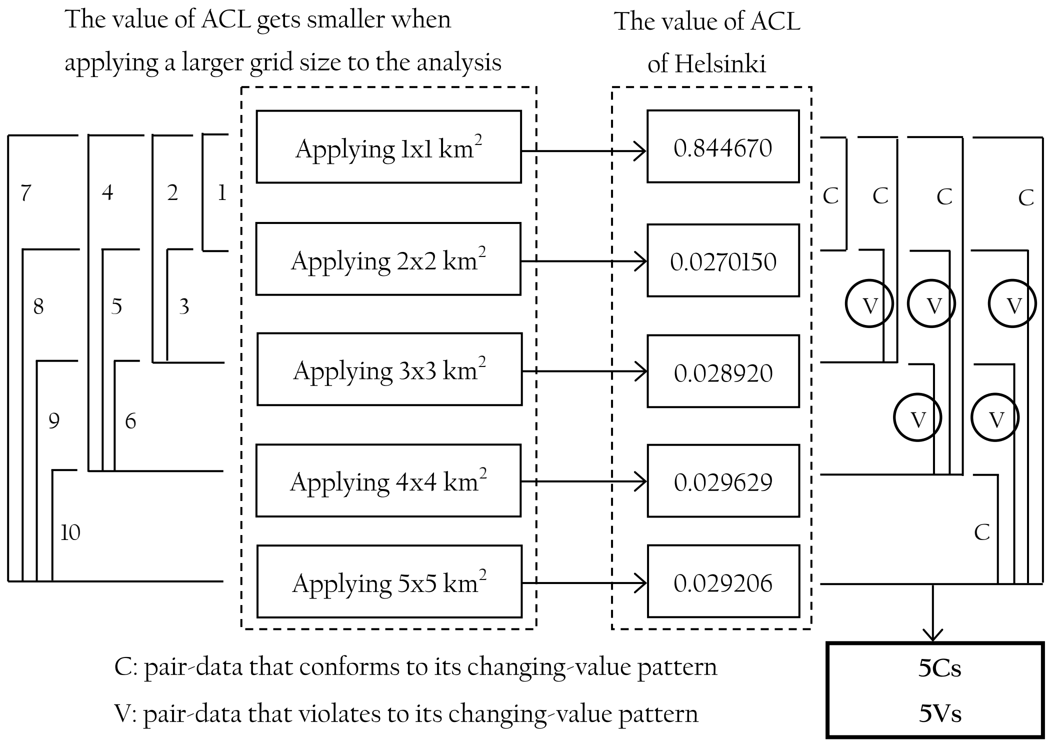


Figure 6.14: Methodology for identifying pair-data that both conform and violate the pattern of changing-degree in the entire dataset (Ω) of ACL taking Helsinki as an example (adopted from Boontore 2011)

Checking for the indicator's ranges and level of stability helps identifying the suitable indicator for every operational dimension of sprawl, except for the operational dimension of 'evenness' and 'exposure' where IOD′, GINI′, AI.5, AI.9, IEI′, INT and ETA′ possess zero amount of Ω. Consequently, two more conditions, the third and fourth conditions in Figure 6.2 are brought into the calculation at this stage.

The third condition shares the same idea with tests for the level of the indicator's stability which is the scale-dependent variable in a real-world geographical context. While the stability test is associated with the consistency in these changes, the third condition pays attention to whether it changes or not. Hence, the indicator that has relatively more cases with no change in its value when applying a different grid size to the analysis will be eliminated from further analysis. The third condition assists in locating ETA′ for the operational dimension of 'exposure'. Still, in the case of 'evenness', IOD′ and AI.5 contain cases that go against the third condition; hence, the fourth condition, relative simplicity in equation structure, is required and IOD′ is selected according to this condition.

Even before the most suitable indicators have been identified for every operational dimension of sprawl, there is another topic we must pursue which is focussed on the most workable grid size for the selected indicators. This is vital for the reason that using too large a grid size in the analysis tends to neglect any details about the urban phenomenon, while applying too small a grid size might not succeed in capturing the overall pattern of spatial variation in this phenomenon.

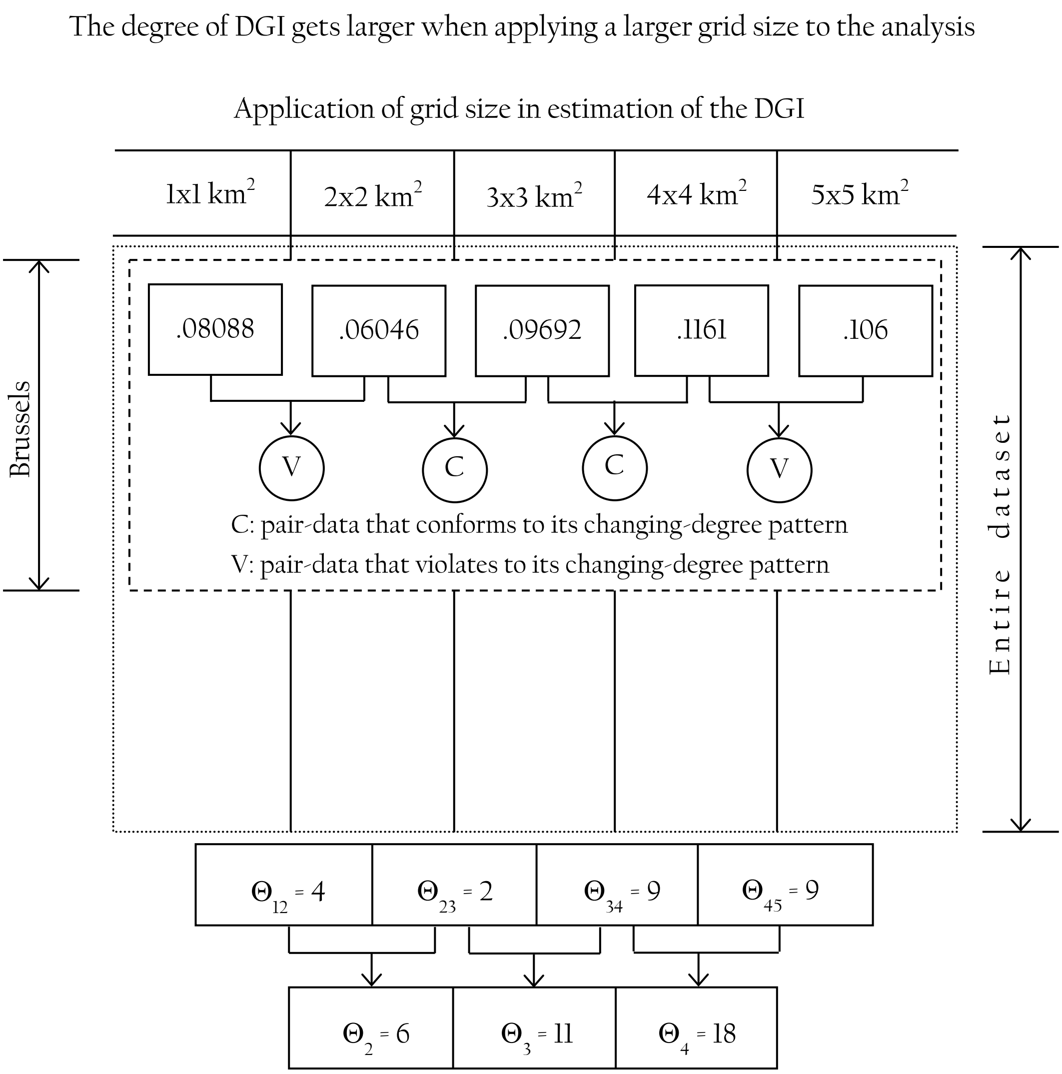


Figure 6.15: Methodology for identifying numbers of adjacent pair-data disagreeing with the pattern of changing-degree in the entire dataset (Θ_{12}, Θ_{23}, Θ_{34} and Θ_{45}), Θ_2, Θ_3 and Θ_4

Table 6.1: Summary of the selection of the indicators for each operational dimension of sprawl

Conceptual Dimension of Sprawl	Operational Dimension of Sprawl	Potential Indicator	Fail to meet condition	Ω	Optimal grid size
1) Density	1.1) Average density	1.1.1) ALD		†	n/a
	1.2) Density Gradient	1.2.1) DGI	C_2	39	
		1.2.2) DGN		20	2x2 km^2
2) Configuration	2.1) Complexity	2.1.1) PAR		†	n/a
		2.1.2) FDS	C_1	†	
		2.1.3) FDB		‡	n/a
	2.2) Clustering	2.2.1) MORAN		†	
		2.2.2) GC′		†	
		2.2.3) ACL	C_1		
		2.2.4) ISP	C_2	11	
		2.2.5) RCL		**8**	**3x3** km^2
	2.3) Centralisation	2.3.1) ACE		11	2x2 km^2
		2.3.2) RCE	C_2	n/a	
3) Composition	3.1) Evenness	3.1.1) IOD′		0	**4x4** km^2
		3.1.2) GINI′	C_3	0	
		3.1.3) AI.1	C_2	1	
		3.1.4) AI.5	C_4	0	
		3.1.5) AI.9	C_3	0	
		3.1.6) IEI′	C_3	0	
		3.1.7) REI	C_2	1	
	3.2) Concentration	3.2.1) DEL		0	**4x4** km^2
		3.2.2) ACO	C_1		
		3.2.3) RCO	C_1		
	3.3) Exposure	3.3.1) INT	C_3	0	
		3.3.2) ETA′		0	**4x4** km^2

† Structure of the equation does not allow for the stability test

‡ Considered as a stable indicator according to its derivation

n/a Not available

In each case study, the direction of the changing-value of the calculated indicator applied for each two adjacent grid sizes, 1x1 km^2 vs. 2x2 km^2, 2x2 km^2 vs. 3x3 km^2, 3x3 km^2 vs. 4x4 km^2 and 4x4 km^2 vs. 5x5 km^2, will be compared to the pattern of the changing-value of its dataset. Numbers of adjacent pair-data disagreeing with the pattern of changing-value of its entire dataset (Θ) will be counted. The total amount of conflicting cases between the applications of two nearby grid sizes used in estimating an indicator will be summed i.e., Θ_{12}, Θ_{23}, Θ_{34} and Θ_{45}. As an example, a grid size of 2x2 km^2 is compared with a grid size of 1x1 km^2 and 3x3 km^2 while Θ_2 is the sum of Θ_{12} and Θ_{23}. Using the same logic, Θ_3 is the sum of Θ_{23} and Θ_{34}, and Θ_4 is the sum of Θ_{34} and Θ_{45} (as we show in Figure 6.15). In the case where two or three of the parameters Θ_2, Θ_3 and Θ_4 are equal, employing a larger grid size is preferable since lesser numbers of cells are created which implies less work in computation. Moreover, it can be seen that there is only one grid size that can be compared with the end of the range grid sizes of 1x1 km^2 and 5x5 km^2. Therefore, practically speaking, in this study, grid sizes of 1x1 km^2 and 5x5 km^2 will not be selected as they can only benefit in deriving Θ_2, Θ_3 and Θ_4.

Table 6.1 summarises the selected indicators with an optimal grid size used for estimating each operational dimension of sprawl. The uncoloured rows emphasise the selected indicators that will be used in modelling sprawl. The letters C_1, C_2, C_3 and C_4 indicate the particular condition that such indicator has been unsuccessful in meeting.

6.3 THE SPRAWL MODEL

In modelling sprawl, the dependent variable is the distance travelled made by private motorised vehicles, while the independent variables are based on the characteristics of the land-use distribution according to the reviewed quantitative attributes of sprawl. From Table 6.1, there are two workable indicators, the PAR and FDB statistics that can be used in estimating the operational dimension of 'complexity', while the MORAN, GC′ and RCL statistics can be used to calculate the dimension of 'clustering'. Therefore, in modelling sprawl, they must be tested separately in six main models as we show from Figures 6.16 to 6.21.

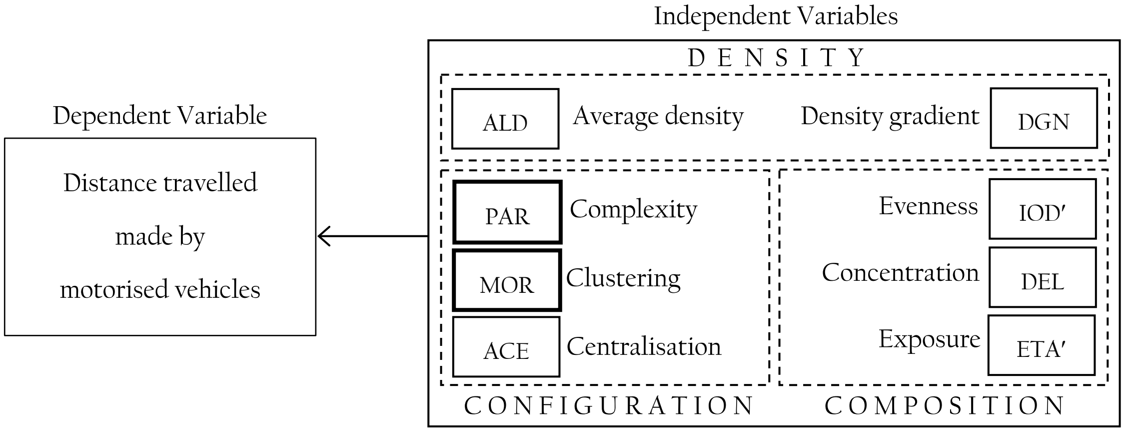


Figure 6.16: The first test of sprawl the model

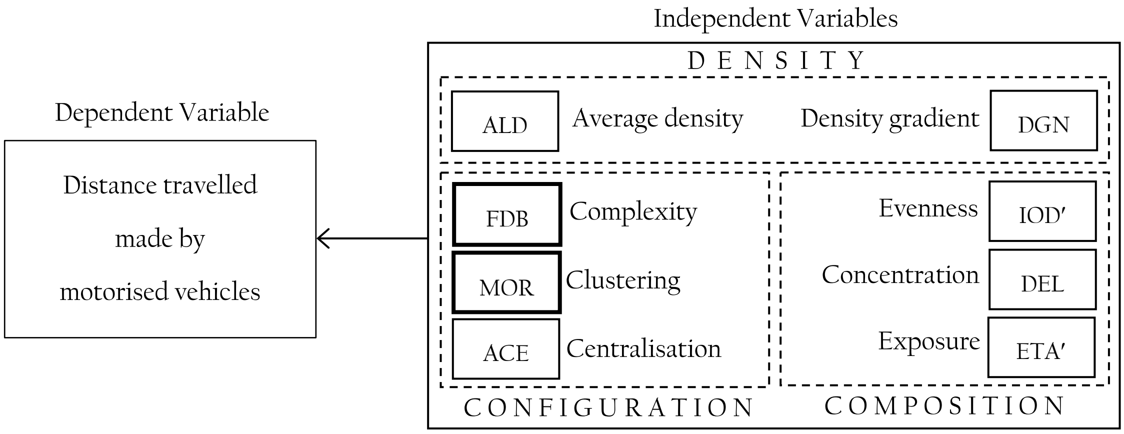


Figure 6.17: The second test of the sprawl model

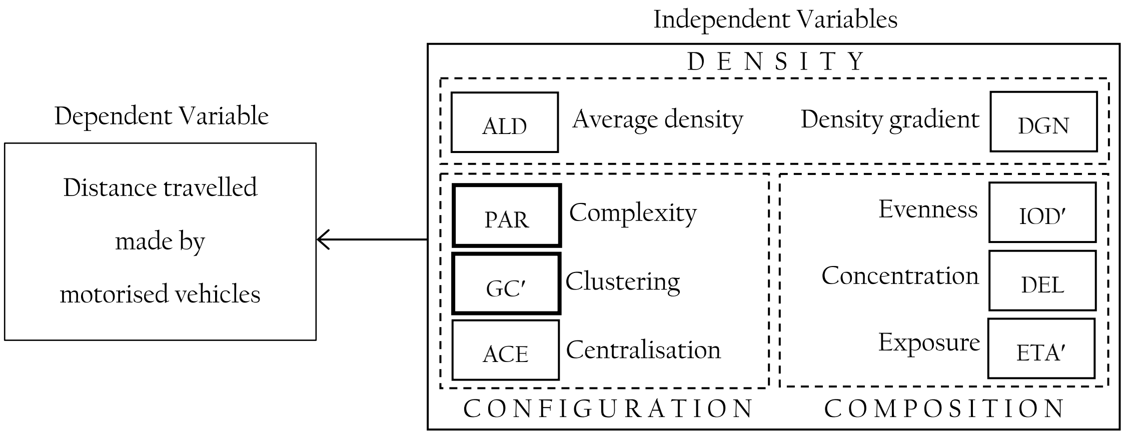


Figure 6.18: The third test of the sprawl model

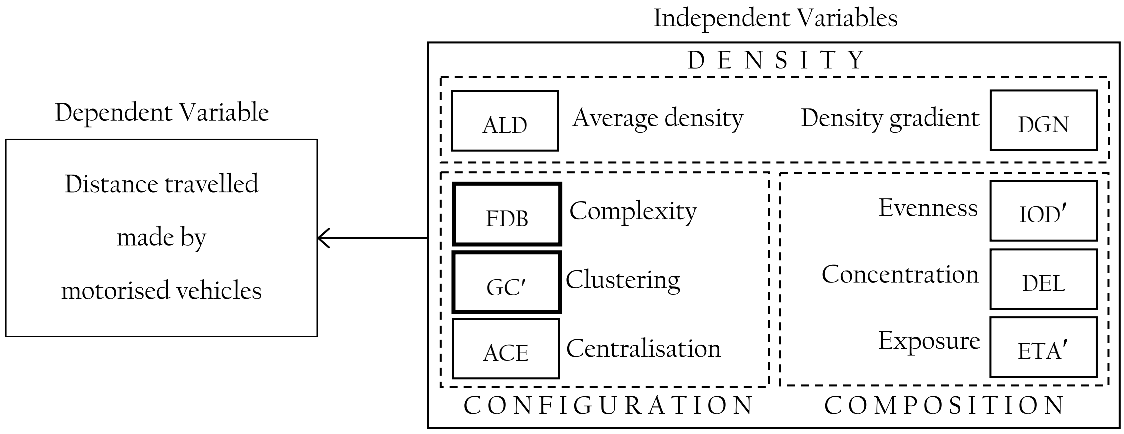


Figure 6.19: The fourth test of the sprawl model

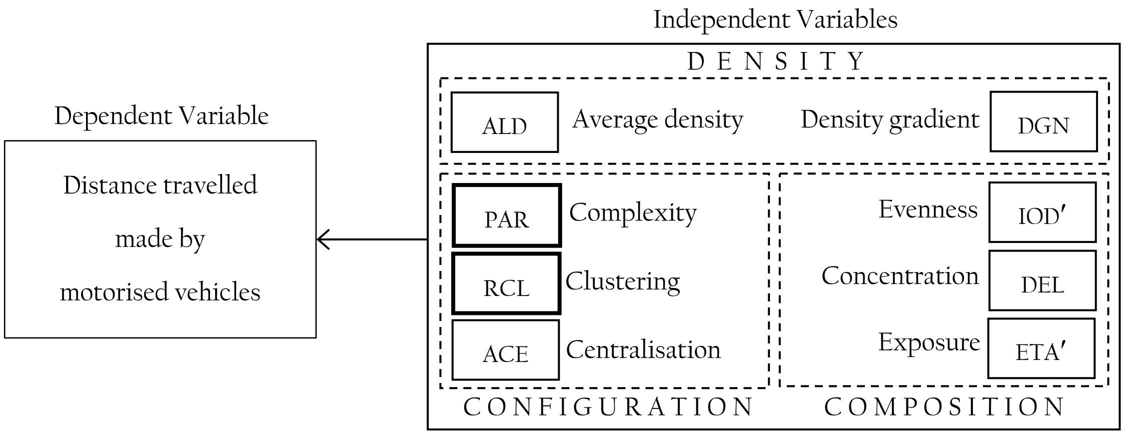


Figure 6.20: The fifth test of the sprawl model

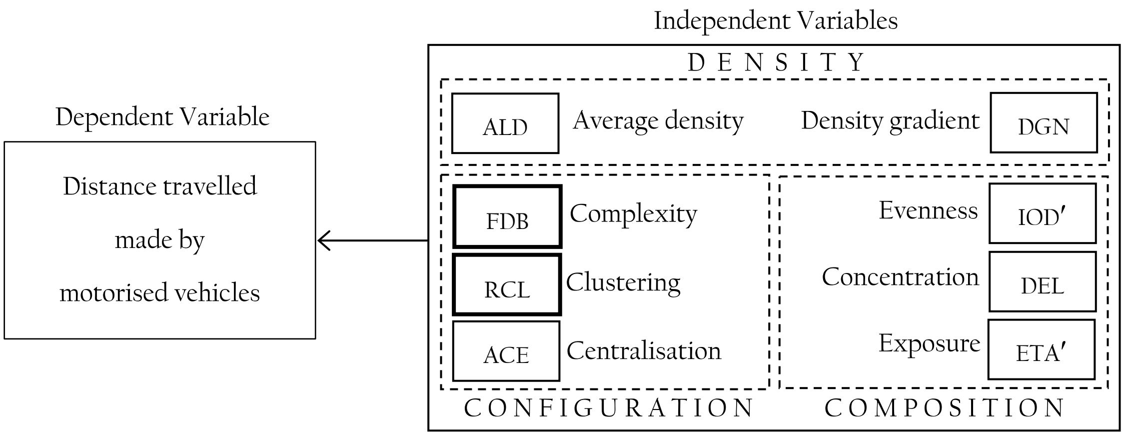


Figure 6.21: The sixth test of the sprawl model

Using the Statistical Package for the Social Sciences (SPSS©), multiple linear regression analysis is employed to model sprawl and this style of model is used for two main reasons. First, such analysis accommodates an investigation of the linear relationship between several ratio-scale independent variables and single ratio-scale dependent variables which completely match with both tested variables in this study. Second, standardised coefficients or beta coefficients are the estimates resulting from multiple regression analysis carried out on variables that have been standardised so that their variances are 1. As a result, standardised coefficients refer to how many standard deviations a dependent variable can change with respect to the standard deviation in the dependent variable. These coefficients in the form of Z-scores perfectly suit the situation of this study where various independent variables are based on different units of measurement.

Multiple linear regression analysis is also used to produce an equation that will predict a dependent variable (Y) using many independent variables (X_1, X_2, X_3,..., X_k), thus giving the real sense of the importance of these variables. This equation has the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + e. \quad (6.1)$$

where β_i are regression coefficients. Statistical estimation and inference in linear regression concentrates on β_i, while *e* is the error term.

In estimating these regression coefficients, sample-data of Y, X_1, X_1,..., X_k is required with a certain sampling size of *n*; therefore, the regression equation (6.1) will be approximated by the following equation:

$$\hat{Y} = a + b_1 X_1 + b_2 X_2 + \ldots + b_k X_k ; \quad (6.2)$$

Consequently, there is always an error in the estimation of Y by $\hat{Y}$ which is called the residual.

The entry of independent variables into the model is based on the stepwise method which is a step-by-step iterative construction of the regression model that engages automatic selection of independent variables based on criteria in which the goodness of fit is always improved. Stepwise regression can be attained by trying out one independent variable at a time, through comparisons of their correlation coefficients, and inclusion of the variable in the model if it is statistically significant. If there is an independent variable already entered into the model, the second independent variable will be taken in, and one can then consider eliminating the independent variables that are already in the model at the same time. This process is repeated until there are no more variables that can be entered or removed and thus the model is complete with the best fit in terms of the various criteria used.

Multiple regression analysis uses the ordinary least squares method of estimating the unknown parameters by minimising the sum of squared 'vertical' distances (in graph terms) between the observed responses in the dataset and the responses predicted by the linear estimation. There are five classical assumptions which determine whether or not the parameters estimated by the least-square technique satisfy the key properties in terms of unbiased, reliable and efficient estimators. First, the error is a random variable with a mean of zero, conditional on the distributions of the independent variables. This condition is always true when the least-square technique is employed. Second, the variance of the errors is constant across levels of the predicted values which require a graphical plot of the residuals versus predicted values to reveal any homoscedasticity. Specifically in SPSS©, it is the plot between standardised residuals on the y-axis versus predicted values on the x-axis and the plot should reveal that the residuals are distributed constantly around zero no matter how the predicted values change to meet this condition (see Figure 6.22). The third assumption is that the errors must be uncorrelated (independence of errors) which can be proved when the value of the Durbin-Watson statistic lies in the range from 1.5 to 2. The normal distribution of residuals satisfies the fourth condition. It can be tested by Shapiro-Wilk statistic, in cases there are 50 sampled values or less; its significance value must be more than 0.05. Fifth, the independent variables must be linearly independent of one another. When there is a linear relationship among the independent variables, this is known as multicollinearity. The problem is that as the degree of multicollinearity increases, the regression model generates coefficients that happen to be unstable and the standard errors for the coefficients begin to increase extensively. This study uses the 'tolerance' values for each independent variable as a test for multicollinearity. The 'tolerance' is an indication of the percent of the variance in an independent variable that cannot be explained by any other independent variables; therefore, the small values, less than 0.1, indicate that an indicator is redundant.

However, our multiple linear regression analysis of the various datasets for the twenty-three European metropolitan areas shows no statistically significant relationships between distance travelled made by private motorised vehicles and the eight quantitative characteristics of land-use distribution in relation to the eight operational dimensions of sprawl. We suspect that the sizes of the metropolitan areas in the form of developable land areas, might affect the results; hence additional tests will try taking samples of out of the analysis one-by-one. Twenty-three European metropolitans areas are listed according to the size of their developable land area from smallest to largest and we show this in Table 6.2.

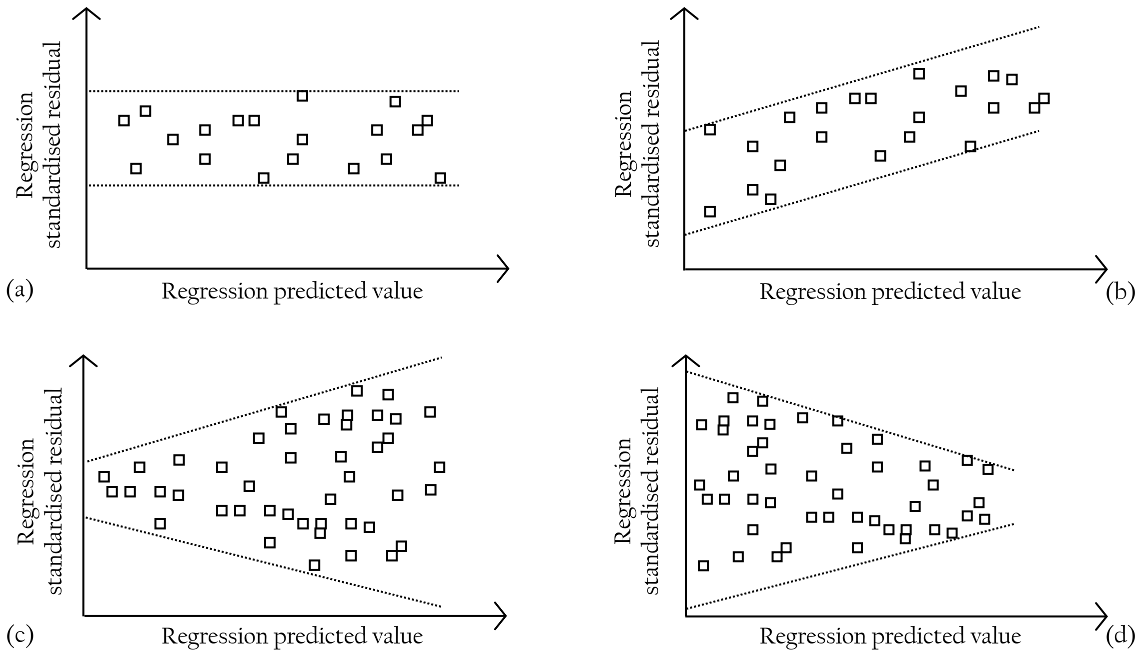


Figure 6.22: Homoscedasticity (a) and (b); Heteroscedasticity (c) and (d) in the plot between regression standardised residuals versus regression predicted values

Table 6.2 : Lists of twenty-three European metropolitan areas sorted by their size of developable land area from smallest to largest

Metropolitan area size rank	**Developable land area (km^2)**	**Metropolitan area size rank**	**Developable land area (km^2)**
1st) Warsaw	1039.33	13th) Stuttgart	10538.17
2nd) Manchester	1293.44	14th) Prague	11208.23
3rd) Athens	2953.95	15th) Paris	11756.68
4th) Lyon	3111.24	16th) Milan	12060.13
5th) Rome	5254.46	17th) Lille	12167.25
6th) Vienna	6180.13	18th) Stockholm	13080.03
7th) Turin	6306.38	19th) Rhein-Ruhr	13864.11
8th) Brussels	6314.70	20th) London	15129.97
9th) Budapest	6759.91	21st) Helsinki	19251.51
10th) Barcelona	7621.58	22nd) Munich	20887.17
11th) Madrid	7863.51	23rd) Berlin	29372.47
12th) Copenhagen	8927.39		

In taking the sample case studies out, we use the 'rule of thumb' that the samples fed in the model must not be less than 60 percent or there must be at least 14 out of 23 samples in the model. In testing for relatively small metropolitan areas, this study removes one sample at a time starting from the largest metropolitan areas, and working vice versa in the case of comparatively large metropolitan areas. Removing case studies from the rank 23rd until the 15th does not produce the promised results and neither does removing the case studies from rank 1 to 9.

Eventually we show that samples from the middle range sizes, from rank 4 to 22, display statistically significant associations between ETA′ and distance travelled made by private motorised vehicles with 0.325, the adjusted R^2. Important statistical measures are displayed in Table 6.3. Exactly similar results are also found in both tests of the model shown in Figures 6.16 and 6.17. The plot between the standardised residuals versus standardised predicted values is presented in Figure 6.23. Most of the errors vary from -1 to around +1.8 in a constant fashion across different levels of the predicted values; therefore, we are clear that heteroscedasticity is not detected in these results.

Table 6.3: Statistically significant relationships found in multiple regression analysis

Dependent variable	Distance travelled made by private motorised vehicles				
Independent variable	ALD, DGN, PAR, RCL, ACE, IOD′, DEL and ETA′ ALD, DGN, FDB, RCL, ACE, IOD′, DEL and ETA′				
Case studies	Metropolitans rank 4th to 22nd				
Adjusted R-Square	0.325				
Standard error of the estimate	2.86905				
***F* statistic**	9.648				
***p*-value**	0.006				
Durbin-Watson	2.359				
Shapiro-Wilk	0.279				
Tolerance	1.000				
	Unstandardised coefficients		**Standardised coefficients**		
	B	**Standard error**	**Beta**	***t***	***p*-value**
Constant	35.308	7.301		4.836	0.000
ETA′	-32.66	10.515	-.602	-3.106	0.006

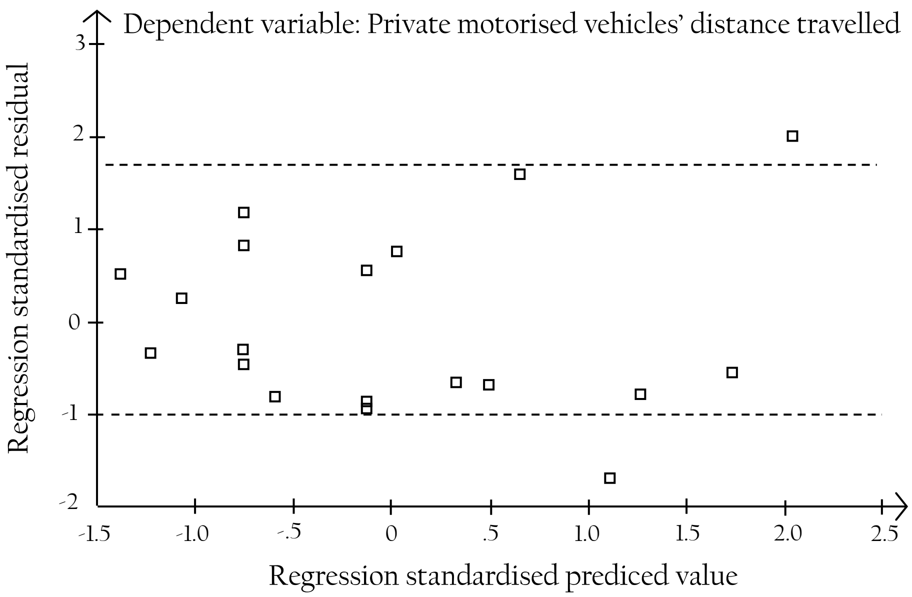


Figure 6.23: Scatter plot between the residuals versus predicted values in relation to the results presented in Table 6.3 (generated from SPSS©)

The test for significance of the whole regression model is carried out using the analysis of variance in the form of ratios between the regression mean square and the error mean square, the *F* statistic, and the *p*-value which all measure significance. Both values shown in Table 6.3 – the F statistic = 9.648 and the p-value at .006 – confirm that there is a linear statistical relationship between the dependent variable and at least one of the independent variables. It should be noted that this study chooses the significance value at 0.05 which means that 95 percent of the time the relationships was observed, it would be judged significant.

The *t* statistic, coupled with its *p*-value, obtained from the results exhibited in Table 6.3, indicate a statistically significant relationship between the dependent variable and the ETA′, and also confirm the significance of both regression coefficients of the constant and of the ETA′ in the multiple linear regression model. Accordingly, the regression equation is

$$Y = 35.308 - 32.66 \cdot \mathrm{ETA}', \tag{6.3}$$

where Y is the private motorised vehicles' distance travelled, while the ETA′ refers to the value of 'adjusted Eta squared'. In summary, such a sprawl model is able to explain 32.5% of the total variation in the distance travelled made by private motorised vehicles.

In modelling sprawl, there are eight independent variables but only twenty-three case studies used, so this study attempts to feed lesser numbers of independent variables into the analysis. Nine independent variables will be selected in order to represent each three main conceptual dimensions of sprawl. There are two valid indicators in the dimension of 'density', six in the dimension of 'configuration' and three in the dimension of 'composition'; therefore, thirty-six combinations of tests can be drawn and put into this further analysis (as is revealed in Figure 6.24).

From thirty-six combinations of tests choosing three independent variables, one for each conceptual dimension of sprawl, only cover the combinations that include the ETA′, show statistically significant relationships to the dependent variable and give similar results to those presented in Table 6.3, thus confirming the importance of ETA′ to the sprawl model. We will explore the implications of all these results in the next chapter.

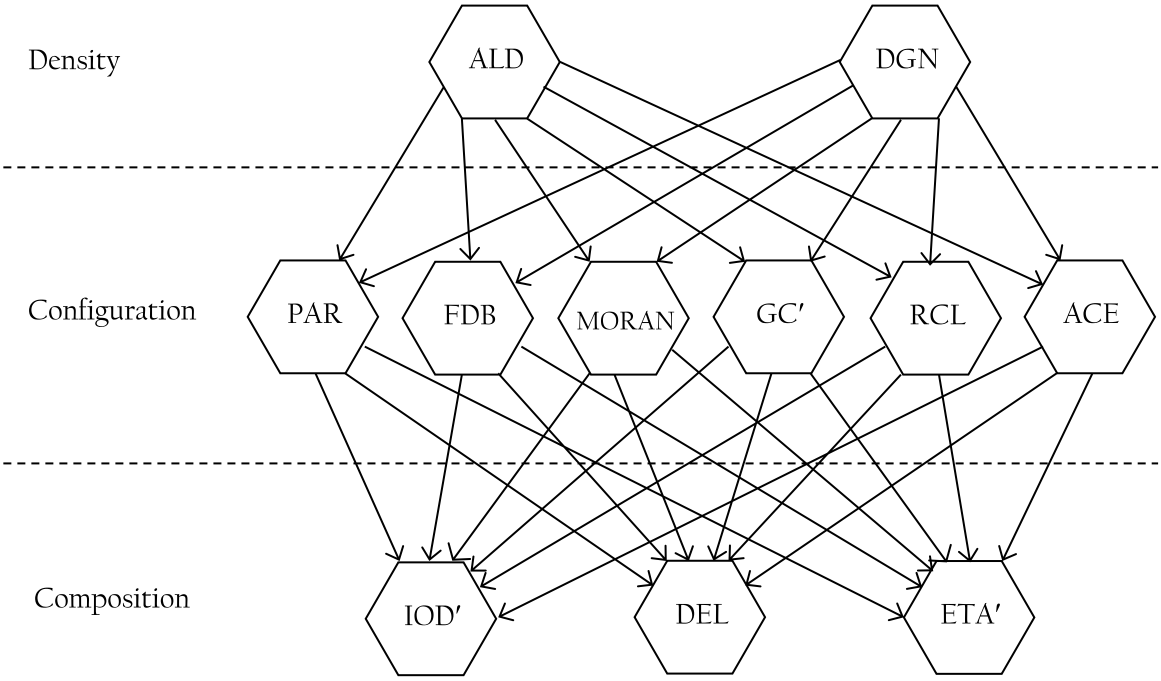


Figure 6.24: Thirty-six combinations used in selecting three independent variables, according to three conceptual dimensions of sprawl, in modelling sprawl

CHAPTER 7: DISCUSSION AND CONCLUSIONS

We will focus on two major areas in this chapter including a discussion of the empirical findings in Section 7.1 and drawing conclusions in relation to the propositions and hypotheses that are basic to this study which we will present in Section 7.2.

7.1 DISCUSSION OF RESULTS

This section is divided into three subsections. Attention is first paid to the issue of the 'effect size' to confirm the reliability of the sprawl model and the simulation of different scenarios of land-use distribution in order to gain in-depth understanding in the dimension of exposure through the value of the ETA′ statistic. Suggestions for future experiments that can be extended from this research are proposed in the last part of this section.

7.1.1 COHEN'S EFFECT SIZE (f^2)

Apart from the adjusted R^2 statistic and the *p*-value of the entire regression presented in Table 6.3, the other statistical measurement worth reporting is the effect size. This is a descriptive statistic that estimates the strength of a relationship without making any statement about whether the apparent relationship in the data reflects a relationship in the population. The effect size facilitates the interpretation of the significance of the obtained model as a complement to inferential statistics, somewhat similar to the *p*-value. It is summarised by different values associated with different fields in Table 7.1.

Table 7.1: Comparisons of the proposed large values of Cohen's f^2 and adjusted R-square in generic behavioural and social science applications and the values obtained from the sprawl model

	Cohen's f^2	**Adjusted R-square**
Behavioural science	0.35	0.26
Social science	larger than 0.35	larger than 0.26
The obtained sprawl model	0.48	0.325

Cohen (1988) proposed the effect size based on the variance explained in a regression. The measure is known as Cohen's f^2, which can be used in the context of the *F*-test for multiple regression analysis. It is defined as:

$$f^2 = \frac{\text{Adjusted R}^2}{1 - \text{Adjusted R}^2}. \tag{7.1}$$

Consequently, using the results from Table 6.3, the value of f^2 for the sprawl model is approximately equal to 0.48. For multiple regression analysis, an f^2 of 0.35 is considered as a large effect size for behavioural science (Cohen 1988) which is equivalent to an adjusted R-square of about 0.26. Cohen (1988) further commented that such criteria will be found to be small in the social science which is the case for this study; however, he did not set specific standards for the large effect size for the disciplines within the social sciences. Hence, based on the calculated effect size, the adjusted R-square and the *p*-value, we have some confidence in the fact that the sprawl model is indeed showing us that distance travelled is key to explaining the degree of sprawl in the different case studies we have engaged with.

7.1.2 Insights into the Agjusted Eta Squared Index

At this stage, the sprawl model, as shown in equation (6.3), can be visualised in terms of the usual 2-D graph which we show in Figure 7.1. Here ETA′, ranges from 0 to +1, and shows a negative relationship with respect to the degree of sprawl. In other words, the degree of sprawl gets larger as the degree/value of ETA′ gets smaller.

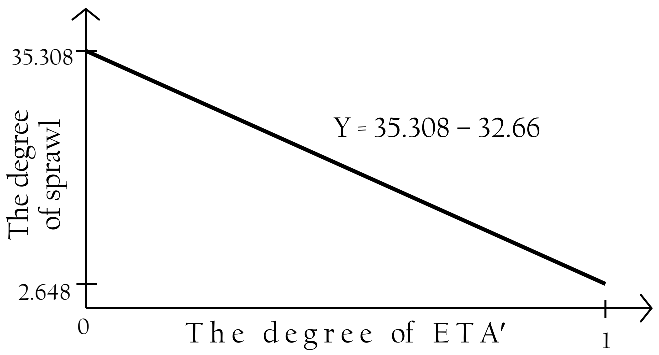


Figure 7.1: Two-dimensional plot of the sprawl model

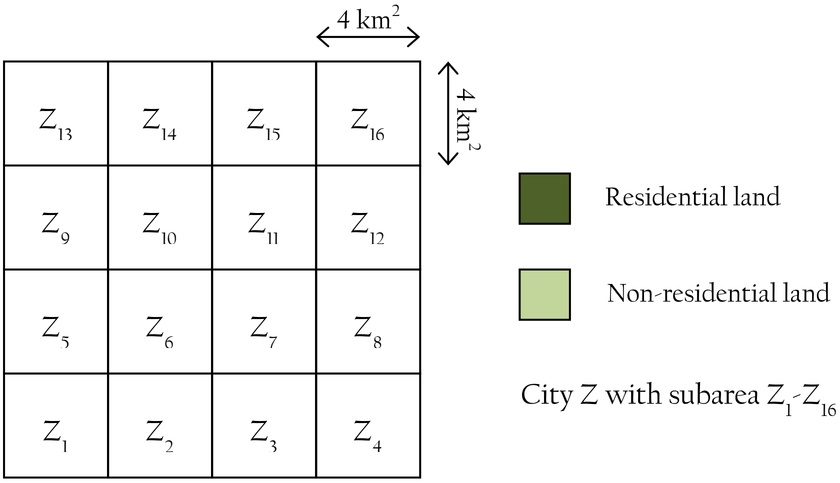


Figure 7.2: City 'Z' and its sixteen subareas

Cross-examination of the various scenarios of land-use distribution and each value of ETA′ provides a greater understanding how the dimension of exposure, in terms of ETA′, behaves in relation to sprawl. Specifically, the dataset of ETA′ is statistically significant in the sprawl model which is derived by tessellating the 4x4 km^2 grid over the land cover maps. Thus similar sizes of square will be used for one subarea in the simulations. For ease of simulation, the city 'Z' contains sixteen subareas and all of them are developable land. A dark green square refers to residential land while a light green square represents non-residential land as we show in Figure 7.2.

As an indicator of exposure, the ETA′ evaluates the degree to which residential and non-residential land uses are exposed to each other by virtue of sharing the same subarea. Initially with such information, the scenarios of homogeneous land use in every subarea will be tested. Figures 7.3(a), (b), (c), (d), (e), (f), (g) and (h) are scenarios where eight subareas fully contain residential land and the other eight contain only non-residential land. This study increases the numbers of subarea with full residential land from eight to twelve subareas shown in Figures 7.4(a) and (b), and decreases subareas with full residential land to four subareas in Figures 7.4(c) and (d). All of these scenarios help confirm that the homogeneity of land uses existing within subareas of 16 km^2, no matter how these subareas locate in relation to others, and these will give a zero degree of ETA′.

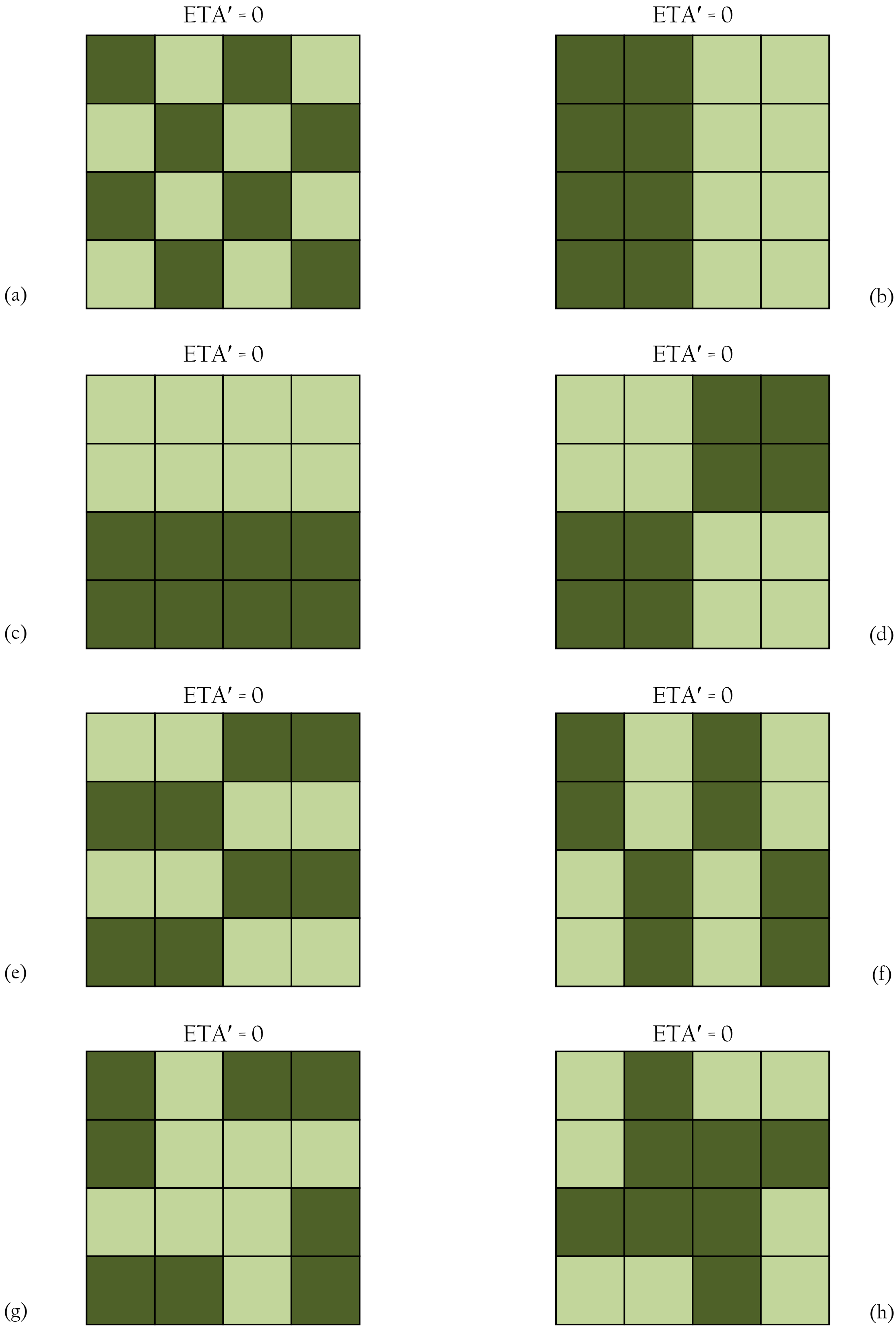


Figure 7.3: Simulations of land-use distribution such that each subarea contains a single land use with equal amounts of residential and non-residential land in total

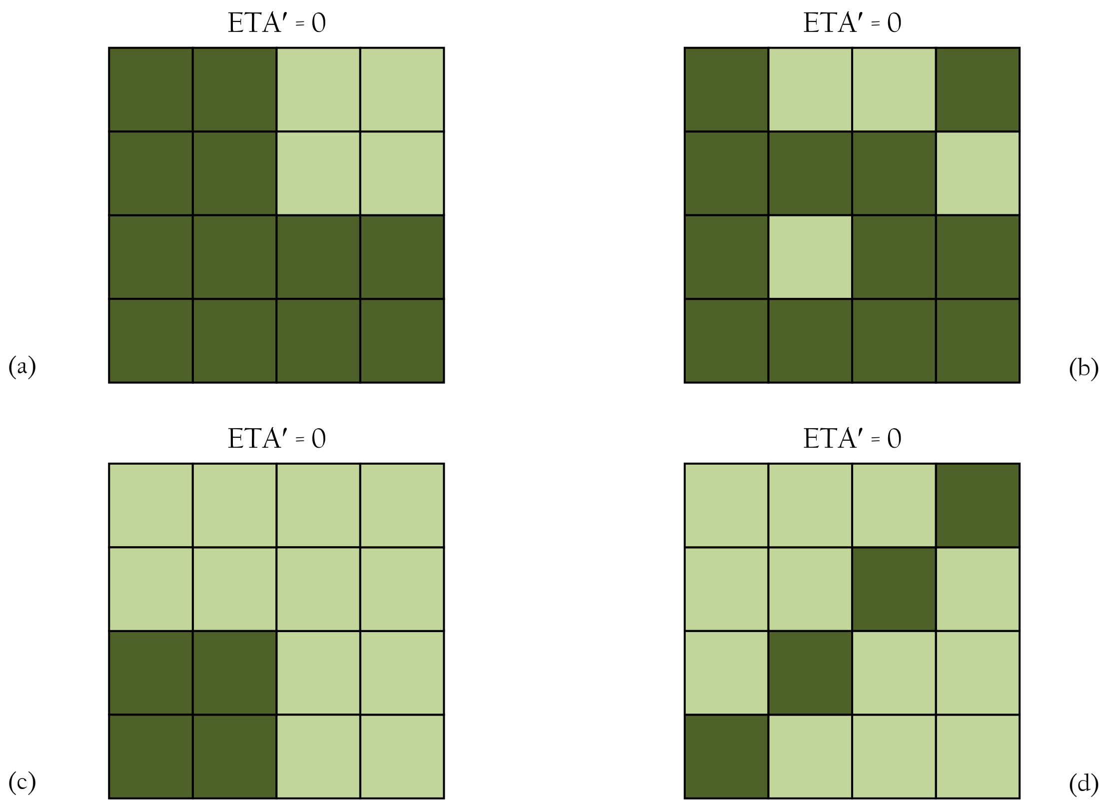


Figure 7.4: Simulations of land-use distribution that have no land-use mix in each subarea with different amounts of residential and non-residential lands in total

This study uses the development of city 'Z' presented in Figure 7.3(d) as a basis for investigation of ten scenarios containing both single-use subareas and mixed-use subareas (as in Figure 7.5). In the mixed-use subareas of each scenario, a specific land use will be controlled over the range to less than or equal to 5%, 25%, 50%, 75% and 95% of other land uses. For example, in the scenario shown in Figure 7.5(a), there are 16 km^2 of residential land in the single-use subareas, while in every other mixed-use subarea, there are less than or equal to 0.9 km^2 of residential land; less than or equal to 4 km^2 of residential land exists in all the mixed-use subareas presented in Figure 7.5(b), and so on. The same method for controlling the amount of land use is also applied to estimate the value of ETA′ for the developments that have only mixed-use subareas as we show in Figure 7.6. It should be noted that different sizes of rectangle are used to represent the areas of any specific land uses in a conceptual way and the amounts of residential and non-residential lands used in each scenario are presented in Appendix I.

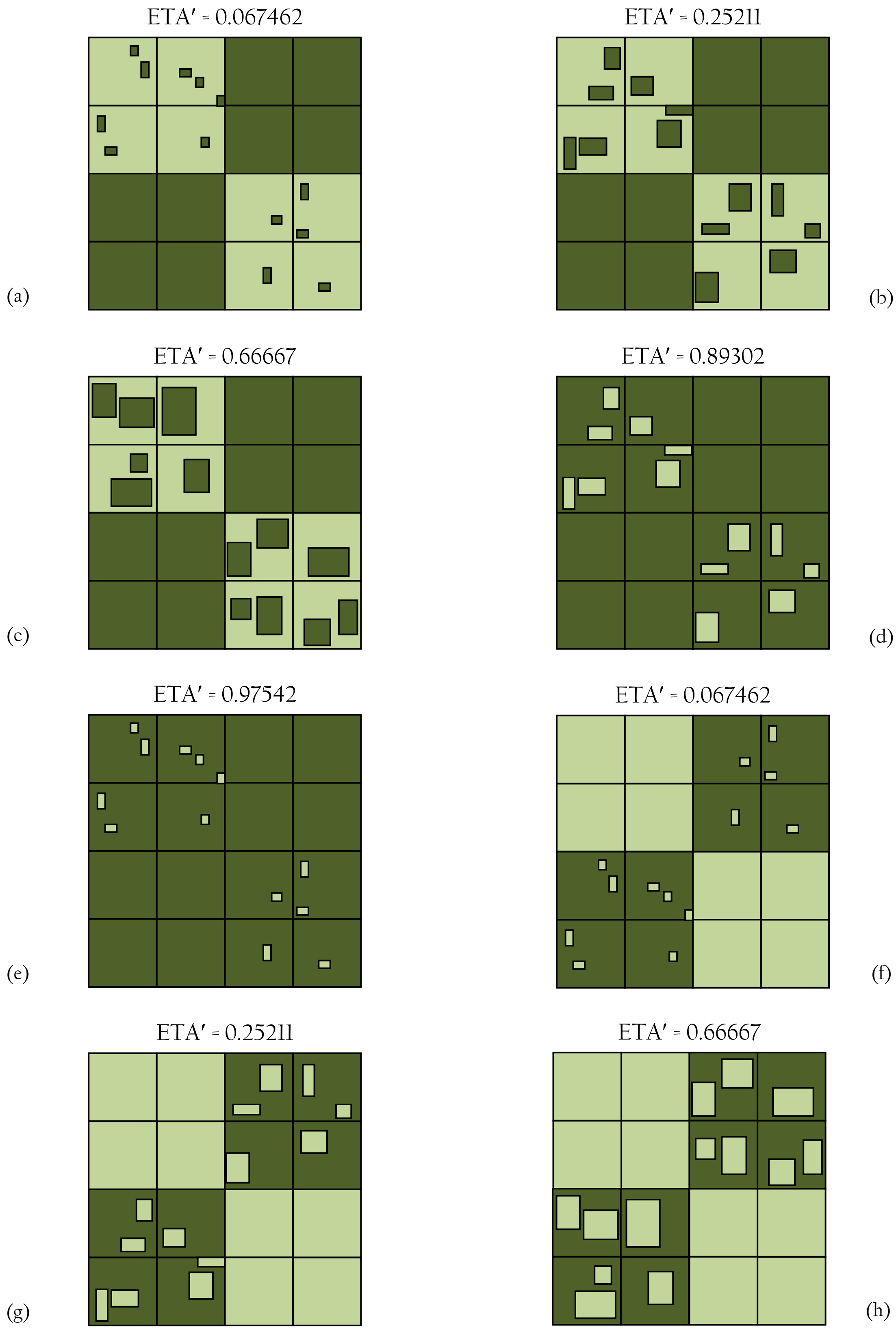


Figure 7.5: Simulations of development containing single-use subareas and mixed-use subareas

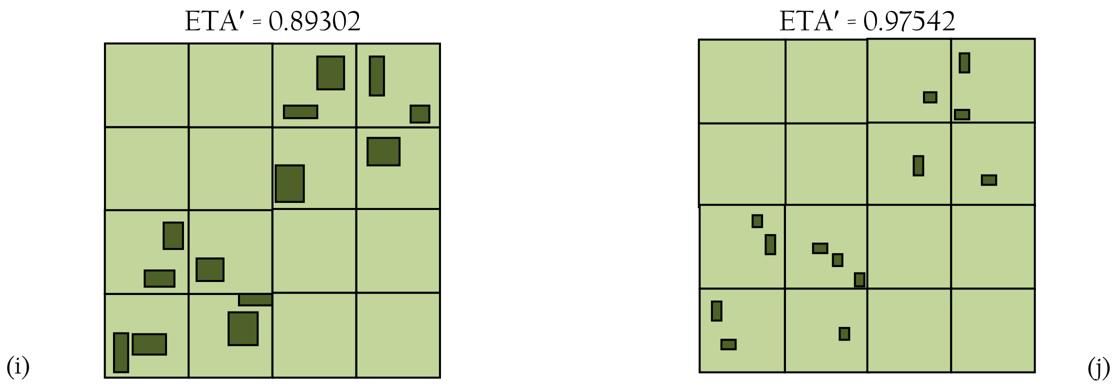


Figure 7.5: Simulations of development containing single-use subareas and mixed-use subareas (continued)

In the scenarios incorporating single-use and mixed-use subareas, it seems that the degree of ETA′ gets higher when the ratio between residential and built-up land of each subarea (ε_i/ψ_i) is equal to each other (see Figures 7.5(e) and (j)). More examination of these developments that contain only mixed-use subareas will be done to verify our speculation that this causes increasing values of ETA′.

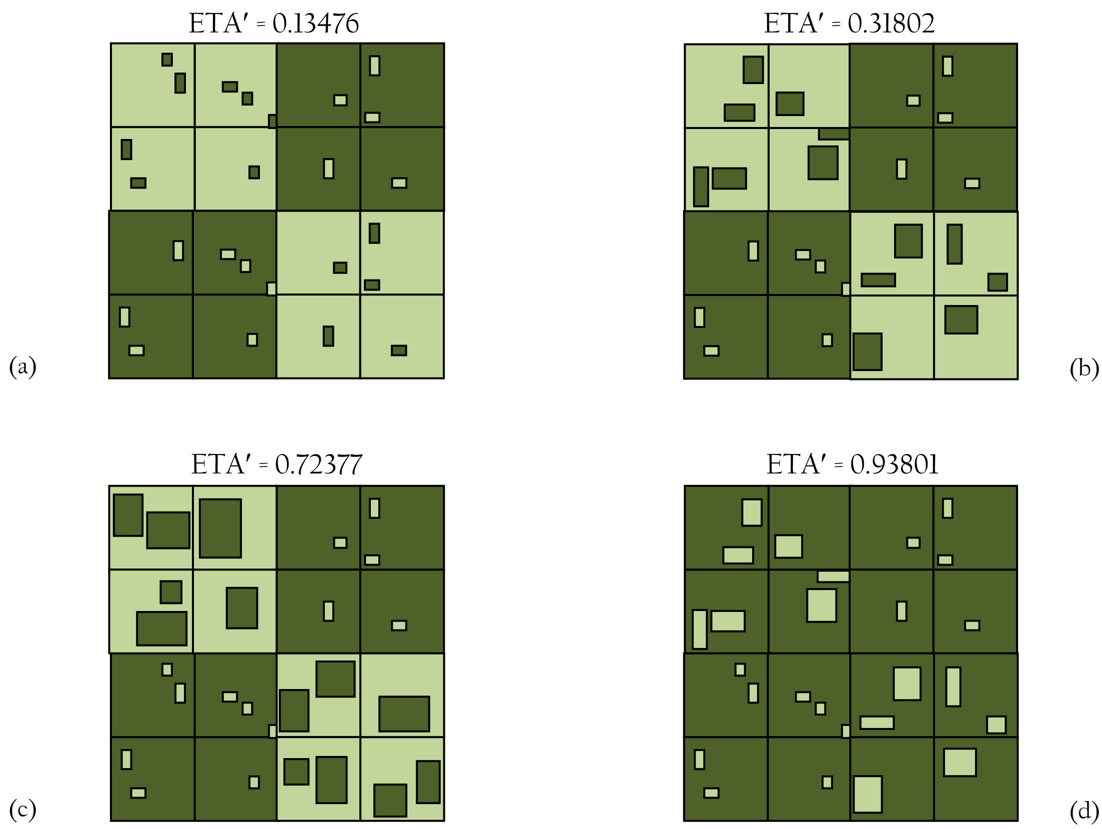


Figure 7.6: Simulations of development containing only mixed-use sub

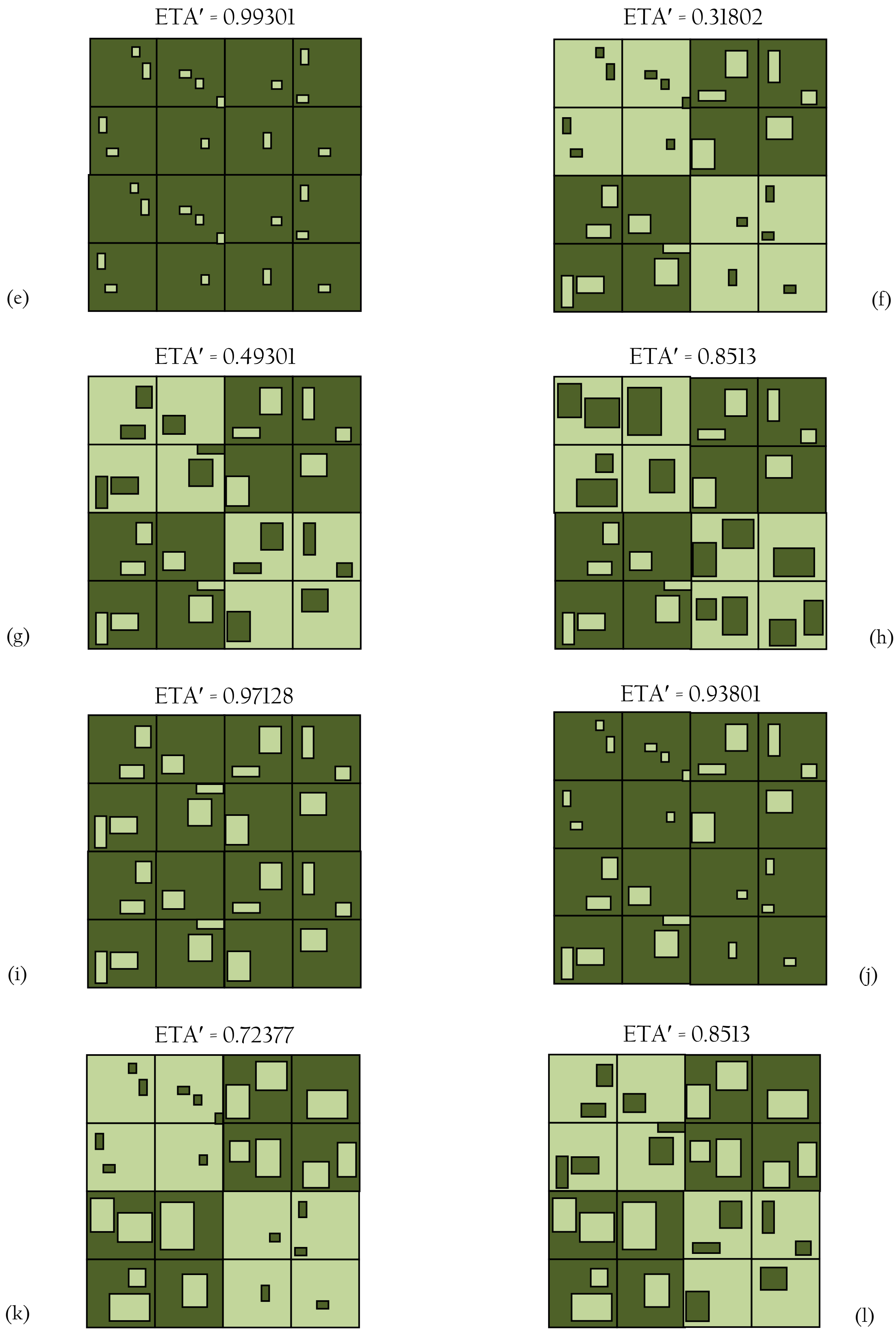


Figure 7.6: Simulations of development containing only mixed-use sub (continued)

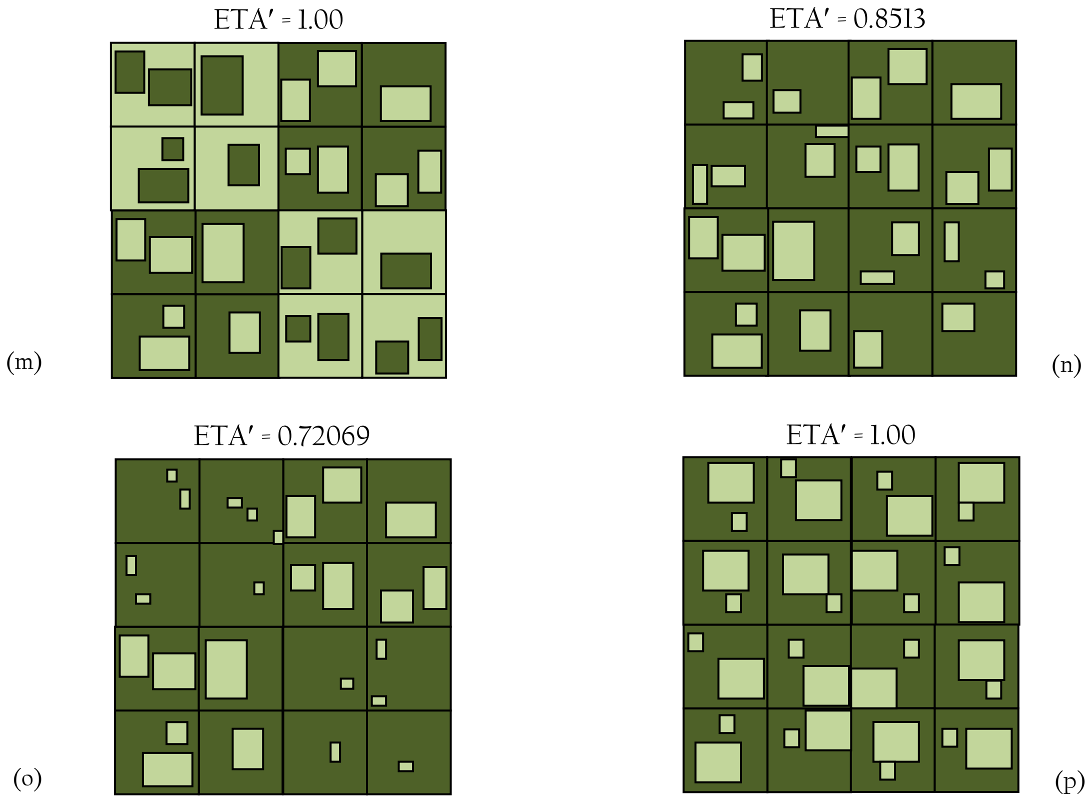


Figure 7.6: Simulations of development containing only mixed-use sub (continued)

Among tests of the scenarios that all subareas in the city are mixed-use, the scenarios shown in Figures 7.6(e) and (i) help confirm the importance of the residential proportion of each subarea (ε_i/ψ_i) in determining the degree of ETA′. In addition, a perfect maximum score of ETA′ will occur when the residential proportion of all subareas are exactly identical which are equal to 0.5 and 0.1875 in the scenario illustrated in Figures 7.6(m) and (p), respectively. In other words, a high degree of sprawl can be obtained when the residential proportion in each subarea of 16 km^2 (ε_i/ψ_i) reflects the residential proportion of the whole city (ε/ψ).

7.1.3 Future Research Proposals

Suggestions for future research related to this study can be extended in two areas. The first area concerns with the extraction of three main data sets from the land cover maps as the inputs used in the calculation of potential indicators of sprawl including: 1) the amount of land area defined by the polygons of land use, 2) length of the boundary lines of polygons, and 3) distance between the polygons. These three numerical data sets are based on residential land use. Results from similar methods but based on the built-up aspects of the city can be used to confirm the proposition that this study has focussed on the vital role of residential characteristics in quantitatively defining urban sprawl.

Among the twenty-three indicators that we have reviewed and used to estimate the operational dimensions of sprawl, seventeen of them require evaluations in two different ways including the comparison of certain spatial properties among subareas, and between subareas and the entire metropolitan area which can be fulfilled by tessellating grid squares over a land cover map. Such a technique is also used in identifying the stability of indicators. There is no rule for identifying the initial location in a grid tessellation and, due to limitations of time, we have arbitrarily tessellated the grid square at the bottom-left corner of the map. Observing the effect from placing the grid squares at different locations is worth trying and, of course, examining the extent to which this changes the data and the model, an average value for each indicator can be obtained from laying five different initial points of grid tessellation as we show in Figure 7.7. Moreover, in testing the stability of each indicator, larger sizes of grid can also be applied to observe the changes.

Figure 7.7: Five different initial positions of the grid tessellation

Finally, the generated model supports in a preliminary sense that assumption that the sizes of the metropolitan areas, in the form of developable land areas, do matter to the framework of this study in attempting to model sprawl (Section 6.2). Different frameworks including previous options proposed in this section are worth testing in order to represent sprawl at other or perhaps at all sizes of metropolitan area. Metropolitan areas with developable land between 3111.24 and 20887.17 km^2 within the European context should be added to the analysis using the same set of independent variables in order to strengthen the meaning of the ETA′ in relation to the operational dimension of 'exposure'. Then, for the purpose of a wider range of applications of the sprawl model, more case studies are selected by using the same criteria of developable size of land but in other geographical contexts, these should be included in the analysis one continent at a time. Moreover, the set of potential indicators along with techniques for identifying the most suitable indicator for each operational dimension of sprawl enables time-series analysis which could allow future studies to investigate the various processes of land development which underpin urban sprawl.

7.2 Concluding Remarks

This last section focuses on the most relevant conclusions that can be derived from this thesis by referring to the propositions and hypotheses of this research. We then conclude with a summation of what this study contributes to knowledge which should be of interest to both researchers and practitioners.

7.2.1 The Most Pertinent Conclusions

Having drawn some conclusions about the sprawl model, in an attempt to intensify the findings of this study, these conclusions will be presented by referring to the propositions and hypotheses of this study but not according to their order listed in Section 1.3. Moreover, four pertinent conclusions and empirical support for the arguments are presented in Table 7.2.

The success in deriving the sprawl model, in general, affirms the fact that the quantitative aspect that the city expresses itself with respect to spatial distribution patterns and differences among land uses. This is the first main hypothesis about urban sprawl that we introduced at the beginning of this study.

Table 7.2: Summary of empirical support for propositions and hypotheses

	Proposition or hypothesis	**Empirical support**
Proposition 1	Sprawl can be measured quantitatively	Fully supported as the sprawl model is obtained
Proposition 2	Sprawl is a multidimensional phenomenon, not just is defined by density characteristics	Supported only for single conceptual dimension of 'exposure'
Hypothesis 1	Distance travelled made by private motorised vehicles is a proxy of sprawl	Fully supported as the sprawl model is obtained
Hypothesis 2	The degree of sprawl derived from its characteristics linearly correlates with the distance travelled made by private motorised vehicles	Supported as the sprawl's effect size is equal to 0.48; adjusted R^2 of 0.325; and *p*-value of 0.006

The main end product of this study, the sprawl model presented in Equation 6.3, empirically helps in confirming the role of distance travelled made by private motorised vehicles as the proxy for sprawl. Through multiple linear regression analysis, it is clear that specific characteristics of land-use distribution can be linked clearly to the corresponding sprawl phenomenon. Specifically, we found that urban sprawl is only a function of the operational dimension of 'exposure' which is estimated by the adjusted Eta squared index. Such an operational dimension reflects the composition aspect which can be referred back to the attribute of a 'single functional use' of sprawl which we introduced in Section 2.6. In other words, this rather supports the second hypothesis of this study that sprawl is not simply defined by the features of density but is still a uni-dimensional phenomenon of homogeneous land use.

7.2.2 A Contribution to Knowledge

This study has provided four important contributions to knowledge. First, it has successfully developed a collection of indicators, which we introduced in Chapter 4 and Table 4.8, that can be used to model sprawl corresponding to the way the city physically demonstrates itself through its geographical distribution of different activities. Furthermore, these potential indicators can be adopted or expanded to investigate other urban phenomena since apart from non-physical aspects, most phenomena and problems of the city also express themselves spatially in the same way that urban sprawl does.

Second, the method for judging for the most relatively stable indicators, which we called the stability test, is a key proposal of this research which we demonstrated in Section 6.2. This can be implemented in circumstances where we work with several different spatial aggregations and thus comparatively stable indicators are required. Such methods also include an objective way of identifying the most suitable sizes of grid tessellation applied to estimate certain indicators.

The main contribution of this thesis is the sprawl model itself, featured in Equation 6.3, where sprawl is modelled in particular way focussing on the 2-D spatial distribution pattern where the model successfully explains 32.5 percent of the variation in sprawl. We realise that other factors, e.g. socio-economic, geologic, geographic, could complete the other 67.5% of the variance to be explained by the model, but to obtain such datasets is not easy in terms of time and resource investments. On the other hand this aggregate sprawl model, even in its static form, requires only land cover maps, which are now quite a widespread resource, and lead to straightforward calculations; however, the generated model builds on the predictive power of distance travelled made by private motorised vehicles which could be exercised in preliminary planning and decision-making or in comparing different urban development scenarios. These are the keys to urban sprawl but they also demonstrate that it is likely that if this conclusion is more widely confirmed, then sprawl would be completely unsustainable because of its use of non-renewable resources and the generation of ever more pollution.

In addition, simulations of several land-uses distribution scenarios related to the degree of 'exposure', estimated by the adjusted Eta Squared index (ETA′), can reveal practical urban development guidelines in relation to the degree of sprawl and we pose these in Section 7.1.2. Practically, a development that possesses similarity with the average residential proportion in the entire city and in each subarea at the scale of 16 km^2 is suggested, while the homogeneity of land use within every subarea of 16 km^2 should be avoided in order to lessen the degree of sprawl.

BIBLIOGRAPHY

Andres, D., Plater-Zyberk, E. & Speck, J., 2000. *Suburban Nation: The Rise of Sprawl and the Decline of the American Dream*, New York: North Point Press.

Batty, M., 1972. Entropy and Spatial Geometry. *Area*, 4(4), pp.230–236.

Batty, M. & Kwang, S.K., 1992. Form Follows Function: Reformulating Urban Population Density Functions. *Urban Studies*, 29(7), pp.1043–1070.

Batty, M., Chin, N. & Besussi, E., 2002. *State of the Art Review of Urban Sprawl Impacts and Measurement Techniques*. http://www.bartlett.ucl.ac.uk/casa/research/past-projects/scatter.

Benevolo, L., 1980. *The History of the City*. Cambridge, MA: MIT Press.

Black, T.J., 1996. The Economics of Sprawl. *Urban Land*, 55(3), pp.6–52.

Boontore, A., 2011a. Stability tests of urban physical form indicators: the case of European cities. In *Procedia Social and Behavioral Sciences*. Spatial Thinking and Geographic Information Sciences 2011. Tokyo, Japan: Elsevier, pp. 336–345.

Boontore, A., 2011b. The Distribution of Land-uses and Distance Travelled in 30 European Cities. In Computers in Urban Planning and Urban Management (CUPUM 2011). Lake Louise, Alberta, Canada.

Brueckner, J.K., 2000. Urban Sprawl: Diagnosis and Remedies. *International Regional Science Review*, 23, pp.160–171.

Bruegmann, R., 2005. *Sprawl: A Compact History*, Chicago: The University of Chicago Press.

Burton, E., 2000. The Compact City: Just or Just Compact? A Preliminary Analysis. *Urban Studies*, 37(11), pp.1969–2001.

Churchman, A., 1999. Disentangling the Concept of Density. *Journal of Planning Literature*, 13(4), pp.389–411.

Clark, D., 2003. *Urban World/Global City*, New York: Routledge.

Cohen, J., 1988. *Statistical Power Analysis for the Behavioral Sciences* Second Edition., New Jersey: Lawrence Erlbaum Associates.

Couch, C., Leontidou, L. & Petsche-Held, G., 2007. *Urban Sprawl in Europe: Landscapes, Land-use Change & Policy*, Blackwell Publishing.

Cox, B.L. & Wang, J.S.Y., 1993. Fractal Surfaces: Measurement and Applications in the Earth Sciences. *Fractals*, 1(1), pp.87–115.

Downs, A., 1999. Some Realities about Sprawl and Urban Decline. *Housing Policy Debate*, 10(4), pp.955–974.

Duffy, M.C., 2003. *Institute of Electrical Engineers: Electric Railways 1880-1990*, London, United Kingdom: The Institution of Engineering and Technology.

European Spatial Planning and Observation Network, 2007. *Study on Urban Functions (Project 1.4.3)*, Luxembourg.Ewing, R., 1994. Characteristics, Causes, and Effects of Sprawl: A Literature Review. *Environmental and Urban Issues*, pp.1–15.

Ewing, R., 1997. Is Los Angeles-style Sprawl Desirable? *Journal of the American Planning Association*, 63(107-126).

Ewing, R., Pendall, R. & Chen, D., 2002. *Measuring Sprawl and Its Impact*, Washington, DC: Smart Growth America.

Ewing, R. & Rong, F., 2008. The Impact of Urban Form on U.S. Residential Energy Use. *Housing Policy Debate*, 19(1), pp.1–30.

Fulton, W., 1996. *The New Urbanism: Hope or Hype for American Communities*, Cambridge, Massachusetts: Lincoln Institute of Land Policy.

Fulton, W. et al., 2001. Who Sprawls Most? How Growth Patterns Differ Across the U.S. http://www.brookings.edu/research/reports/2001/07/metropolitanpolicy-fulton.

Galster, G. et al., 2001. Wrestling Sprawl to the Ground: Defining and Measuring an Elusive Concept. *Housing Policy Debate*, 12(4), pp.681–717.

Gans, H.J., 1967. *The Levittowners: Ways of Life and Politics in a New Suburban Community*, London: Allen Lane The Penguin Press.

Garcia-Palomares, J.C., 2010. Urban sprawl and travel to work: the case of metropolitan area of Madrid. *Journal of Transport Geography*, 18, pp.197–213.

Gillham, O., 2002. *The Limitless City: A Primer on the Urban Sprawl Debate*, London: Island Press.

Gordon, P. & Richardson, H.W., 1997. Are Compact Cities a Desirable Planning Goal? *Journal of the American Planning Association*, 63(1), pp.1–12.

Great Britain. Royal Commission on the Distribution of the Industrial Population, 1945. *Report of the Royal Commission on the Distribution of the Industrial Population/chairman Sir Montague-Barlow*, London: H.M. Stationery Office.

Guerois, M. & Pumain, D., 2008. Built-up encroachment and the urban field: a comparison of forty European cities. *Environment and Planning A*, 40, pp.2186–2203.

Hall, P., 1997. *Cities of Tomorrow: An Intellectual History of Urban Planning and Design in the Twentieth Century*, Oxford: Blackwell Publishers.

Hall, P., 2002. *Urban and Regional Planning* 4th ed., London: Routledge.

Hasse, J.E. & Lathrop, R.G., 2003. Land resource impact indicators of urban sprawl. *Applied Geography*, 23, pp.159–175.

Jenks, M., Burton, E. & Williams, K., 1996. *The Compact City: A Sustainable Urban Form?*, London: E & FN Spon.

Lam, N.S. & Cola, L.D., 1993. *Fractals in Geography*, New Jersey: PTR Prentice-Hall.

Lessinger, J., 1962. The Case for Scatterization. *Journal of the American Institute of Planners*, 28(3), pp.159–169.

Longley, P.A., Batty, M. & Chin, N., 2002. Sprawling Cities and Transport: Preliminary Findings from Bristol, UK. Available at: http://www.ersa.org/ersaconfs/ersa02/cd-rom/papers/137.pdf .

Lopez, R. & Hynes, P.H., 2003. Sprawl In The 1990s: Measurement, Distribution, and Trends. *Urban Affairs Review*, 38(3), pp.325–355.

Mandelbrot, B., 1967. How Long Is the Coast of Britain? Statistical Self-Similarity and Fractional Dimension. *Science*, 156(3775), pp.636–638.

Mandelbrot, B., 1977. *Fractals: Form, Chance, and Dimension*, San Francisco: W.H. Freeman and Company.

Mandelbrot, B., 1982. *The Fractal Geometry of Nature*, United States: W. H. Freeman and Company.

Malpezzi, S. & Guo, W.-K., 2001. Measuring 'sprawl': Alternative Measures of Urban Form in U.S. Metropolitan Areas, http://www.citeulike.org/user/jrblack/article/6170828.

Massey, S.D. & Denton, A.N., 1988. The Dimensions of Residential Segregation. *Social Forces*, 67(2), pp.281–315.

Mesev, T.V. et al., 1995. Morphology from imagery: detecting and measuring the density of urban land use. *Environment and Planning A*, 27(5), pp.759–780.

Mieszkowski, P. & Mills, E.S., 1993. The Causes of Metropolitan Suburbanization. *Journal of Economics Perspectives*, 7(3), pp.135–147.

Morris, A.E.J., 1994. *A History of Urban Form: Before the Industrial Revolutions* 3rd ed., London: Longman.

Mumford, L., 1968. *The City in History: Its Origins, Its Transformations, and Its Prospects* 1st ed., New York: Mariner Books.

Nechyba, T.J. & Walsh, R.P., 2004. Urban Sprawl. *The Journal of Economic Perspective*, 18, pp.177–200.

Newman, P., 1992. The Compact City: An Australian Perspective. *Built Environment*, 18(4), pp.285–300.

O'Neill, R.V. et al., 1988. Indices of Landscape Pattern. *Landscape Ecology*, 1(3), pp.153–162.

Organisation for Economic Co-operation and Development, 2006. *OECD Territorial Reviews. Competitive Cities in the Global Economy*, OECD Publishing.

Osborn, F.J. & Whittick A., 1963. *The New Towns: The Answer to Megalopolis*, Dublin: Hely Thom.

Ottensmann, J.R., 1977. Urban Sprawl, Land Values, and the Density of Development. *Land Economics*, 53(4), pp.389–400.

Peiser, R., 1989. Density and Urban Sprawl. *Land Economics*, 65(3), pp.193–204.

Peiser, R., 2001. Decomposing Urban Sprawl. *Town Planning Rreview*, 76(3), pp.275–298.

Pendall, R., 1999. Do Land Use Controls Cause Sprawl. *Environmental and Planning B*, 26(4), pp.555–571.

Phelps, N.A. et al., 2006. *Post-Suburban Europe: Planning and Politics at the Margins of Europe's Capital Cities*, London: Palgrave Macmillan.

Razin, E. & Rosentraub, M., 2000. Are Fragmentation and Sprawl Interlinked? : North American Evidence. *Urban Affairs Review*, 35, pp.821–836.

Real Estate Research Corporation, 1974. *The Costs of Sprawl: Environmental and Economic Costs of Alternative Residential Development Patterns at the Urban Fringe*, US Environmental Protection Agency, Washington, DC.

Silva, A.N.R. da, Costa, G. Camargo F. & Brondino, N.C.M., 2007. Urban sprawl and energy use for transportation in the largest Brazilian cities. *Energy for Sustainable Development*, 11(3), pp.44–50.

Steadman, P. et al., 2000. A Classification of Built Forms. *Environment and Planning B: Planning and Design*, 27(1), pp.73–91.

The International Association of Public Transport (UITP) & Institute for Sustainability and Technology Policy (ISTP), 1995. UITP Millennium Cities Database for Sustainable Transport: Urban Transport, Landuse, Infrastructure, Economic and Environmental Indicators for 100 International Cities.

Tiebout, C.M., 1956. A Pure Theory of Local Expenditures. *Journal of Political Economy*, 64(5), pp.416–424.

Torrens, P.M. & Alberti, M., 2000. Measuring Sprawl, CASA working paper

Transportation Research Board, N.R.C., 1998. The Cost of Sprawl-Revisited.

Tsai, Y.-H., 2005. Quantifying Urban Form: Compactness versus 'Sprawl'. *Urban Studies*, 42(1), pp.141–161.

Turner, M.G., 1989. Landscape Ecology: The Effect of Pattern on Process. *Annual Review of Ecological Systems*, 20, pp.171–197.

United Nation: Department of Economic and Social Affairs, 2008. Demographic Yearbook 2006.

United Nations: Department of Economic and Social Affairs: Population Division, 2009. World Population Prospects: The 2008 Revision.

United Nations Environment Programme (UNEP), 2002. Global Environment Outlook 3: Past, present and future perspectives.

van Andel, J., 1998. Children's Use of Neighborhood Public Space in Relation to Density.

Wassmer, R.W., 2001. The Connection between Local Government Finance and the Generation of Urban Sprawl in California, www.csus.edu/calst/government_affairs/reports/ffp44.pdf .

Wheeler, S.M., 2000. Planning for Metropolitan Sustainability. *Journal of Planning Education and Research*, 20(2), pp.133–145.

White, M.J., 1983. The Measurement of Spatial Segregation. *American Journal of Sociology*, 88(5), pp.1008–1018.

Wolman, H. et al., 2005. The Fundamental Challenge in Measuring Sprawl: Which Land Should Be Considered? *The Professional Geographer*, 57(1), pp.94–105.

World Commission on Environment and Development, 1987. *Our Common Future*.

World Resources Institute, 1994. *World Resources 1994-1995: A Guide to the Global Environment*, Available at: http://www.abebooks.com/World-Resources-1994-1995-Guide-Global-Environment/764631939/bd.

World Resources Institute, 2000. *A Guide to World Resources 2000-2001: People and Ecosystems: The Fraying Web of Life*, Available at: http://www.wri.org/publication/world-resources-2000-2001-people-and-ecosystems-fraying-web-life.

www.eea.europa.eu/themes/landuse/interactive/clc-download, accessed 20/3/2014.

www.vdstech.com/map_data.htm, accessed 20/3/2014.

Zeigler, D.J., Brunn, S.D. & Williams, J.F., 2003. *Cities of the World: World Regional Urban Development*, New York: Rowman & Littlefield Publishers.

APPENDIX A: EU METROPOLITAN AREAS

The European metropolitan areas listed by the Organisation for Economic Cooperation and Development (OECD).

Country	Metropolitan area	Units included
Austria	1) Vienna	Wein
		Wein-Umgebung
		Weiner Umland-Nordteil: Ganserndorf, Korneuburg, Mistelbach, Tulln
		Weiner Umland-Sudteil: Baden, Bruck an der Leitha, Modling
Belgium	2) Brussels	Brussels
		Brabant Wallon
		Oost-Vlaanderen (East Flanders)
		Vlaams Brabant (Flemish Brabant)
Czech Republic	3) Prague	Praha (Prague)
		Stredocesky
Denmark	4) Copenhagen	Frederiksborg amt
		Kobenhavns amt (Copenhagen county)
		Roskilde amt
		Storstroms amt
		Vestsjellands amt
Finland	5) Helsinki	Ita-Uusimaa (Eastern Uusimaa)
		Kanta-Hame (Travastia Proper)
		Paijat-Hame (Paijanne Tavastia)
		Uusimaa

Country	Metropolitan area	Units included
France	6) Lille	Nord (Nord-Pas-de-Calais)
	7) Lyon	Rhone
	8) Paris	Essonne
		Hauts-de-Seine
		Paris
		Seine-et-Marne
		Seine-Saint-Denis
		Val-de-Marne
		Val-de-Oise
		Yvelines
Germany	9) Berlin	Berlin
		Havelland-Flaming: Brandenburg an der Havel Stadte, Havelland, Potsdam-Mittlemark, Potsdam Stadte, Tetlow-Flaming
		Lausitz-Spreewald: Cottbus Stadte, Dahme-Spreewald, Elbe-Elster, Overspreewald-Lausitz, Spree-Neisse
		Oderland-Spree: Frankfurt am Oder Stadte, Markisch-Oderland, Oder-Spree
		Prignitz-Oberhavel: Oberhavel, Ostprignitz-Ruppin, Prignitz
		Uckermark-Barnim: Barnim, Uckermark

Country	Metropolitan area	Units included
Germany	10) Frankfurt	Mittelhessen: Giessen, Lahn-Dill-Kreis, Limburg-Weilburg, Marburg-Biedenkopf, Vogelsbergkreis
		Osthessen
		Rhein-Main: Damstadt Stadte, Frankfurt am Main State, Hochtaunuskreis, Main-Kinzig, Main-Taunus, Offenbach, Offenbach am Main Stadte, Rheingau-Taunus, Wetteraukreis, Wiesbaden Stadte
		Bayerischer Untermain
		Starkenburg: Bergstrasse, Damstadt-Dieburg, Gross-Gerau, Odenwakdkreis
	11) Hamburg	Hamburg
		Schleswig-Holstein Sud-West
		Schleswig-Holstein Sud
		Bremenrhaven
		Sudheide
		Luneburg
	12) Munich	Augsburg
		Ingolstagt
		Landshut
		Munchen
		Oberland
		Regensburg
		Sudostoberbayern

Country	Metropolitan area	Units included
Germany	13) Rhein-Ruhr	Aachen
		Bochum/Hagen
		Bonn
		Dortmund
		Duisburg/ Essen
		Dusseldorf
		Emscher-Lippe: Bottrop, Galsenkirchen, Recklinghausen
		Koln
Germany	14) Stuttgart	Stuttgart
Greece	15) Athens	Attiki
Hungary	16) Budapest	Budapest
		Pest
Ireland	17) Dublin	Dublin
		Mid-East: Meath, Kildare, Wicklow
Italy	18) Milan	Novara
		Varese
		Como
		Lecco
		Milano
		Bergamo
		Pavia
		Lodi

Country	Metropolitan area	Units included
Italy	19) Naples	Napoli
	20) Rome	Roma
	21) Turin	Torino
Netherlands	22) Randstad	Utrecht Noord-Holland Zuid-Holland Flevoland
Norway	23) Oslo	Oslo Akershus Ostfold Buskerud
Poland	24) Krakow	Krakowsko-Tarnovski M. Krakow (Krakow City)
	25) Warsaw	Warsawski M. Warsawski (Warsaw City)
Portugal	26) Lisbon	Grande Lisboa: Amadora, Cascais, Lisboa, Loures, Mafra, Odivelas, Oeiras, Sintra, Vila Franca de Xira Peninsula De Setubal: Alcochete, Almada, Barreiro, Moita, Montijo, Palmela, Seixal, Sesimbra, Setubal
Spain	27) Barcelona	Barcelona
	28) Madrid	Comunidad de Madrid
	29) Valencia	Comunidad de Valencia

Country	Metropolitan area	Units included
Sweden	30) Stockholm	Stockholm
		Uppsala Ian
Switzerland	31) Zurich	Aargau
		Zurich
		Luzern
		Zug
Turkey	32) Ankara	Ankara
	33) Istanbul	Istanbul
		Kocaeli
		Yalova
	34) Izmir	Izmir
United Kingdom	35) Birmingham	Birmingham
		Solihull
		Coventry
		Dudley and Sandwell
		Walsall and Wolverhampton
	36) Leeds	Bradford
		Leeds
		Calderdale, Kirklees, Wakefield

Country	Metropolitan area	Units included
United Kingdom	37) London	Inner London: Camden, Greenwich, Hackney, Hammersmith and Fulham, Islington, Kensington and Chelsea, Lambeth, Lewisham, Southwark, Tower Hamlets, Wandsworth, Westminster
		Outer London: Barking and Dagerham, Bexley, Brent, Bromley, Croydon, Ealing, Enfield, Haringey, Harrow, Havering, Hillingdon, Hounslow, Kingston upon Thames, Merton, Newham, Redbridge, Richmond upon Thames, Sutton, Waltham Forest
		Hertfordshire
		Southend-on-Sea
		Thurrock
		Essex
		Berkshire
		Milton Keynes
		Buckinghamshire
		Surrey
		Medway Towns
		Kent
	38) Manchester	Greater Manchester: Manchester, Stockport, Tameside, Oldham, Rochdale, Bury, Bolton, Wigan, Salford, Trafford

APPENDIX B: CATEGORY OF LAND USES

Forty-four types of land uses embedded in the CORINE land cover maps, European Environment Agency (EEA), are grouped into: 1) residential land use, 2) non-residential land use, 3) lands that can be developed and 4) land that cannot be developed.

Land-use category	Code	Land-use class
Residential land use	111	Continuous urban fabric
	112	Discontinuous urban fabric
Non-residential land use	121	Industrial or commercial units
	123	Port areas
	124	Airports
	141	Green urban areas
	142	Sport and leisure facilities
Developable land		Residential land-use
		Non-residential land-use
	133	Construction sites
	211	Non-irrigated arable land
	212	Permanently irrigated land
	213	Rice fields
	221	Vineyards
	222	Fruit trees and berry plantations
	223	Olive groves
	231	Pastures
	241	Annual crops associated with permanent crops
	242	Complex cultivation patterns
	243	Agro-forestry areas

Land-use category	Code	Land-use class
Developable land	244	Land principally occupied by agriculture, with significant areas of natural vegetation
	311	Broad-leaved forest
	312	Coniferous forest 313 Mixed forest
	321	Natural grasslands
	322	Moors and heathland
	323	Sclerophyllous vegetation
	324	Transitional woodland-schrub
	333	Sparsely vegetated areas
Un-developable land-use	122	Road and rail networks and associated land
	131	Mineral extraction sites
	132	Dump sites
	331	Beaches, dunes, sands
	332	Bare rocks
	334	Burnt areas
	335	Glaciers and perpetual snow
	411	Inland marshes
	412	Peat bogs
	421	Salt marshes
	422	Salines
	423	Intertidal flats
	511	Water courses
	512	Water bodies
	521	Coastal lagoons
	522	Estuaries
	523	Sea and ocean

APPENDIX C: DATA ON DAILY TRIPS PER CAPITA

The transport data on daily trips per capita for the year 1995 was collected by the International Association of Public Transport (UITP) and Institute for Sustainability and Technology Policy (ISTP).

Country	Metropolitan area	Average numbers of daily trip (trips/capita)			
		Public modes	Private modes	Mechanised modes	Total
Austria	Graz	0.58	1.49	0.45	3.20
	Vienna	0.86	1.19	0.11	2.86
Belgium	Brussels	0.48	1.12	0.00	2.55
Denmark	Copenhagen	0.46	1.61	0.52	2.97
Finland	Helsinki	0.58	1.58	0.28	2.92
France	Lille	0.25	2.15	0.07	0.35
	Lyon	0.40	1.97	0.03	3.53
	Marseille	0.41	1.70	0.02	3.33
	Nantes	0.42	1.85	0.08	3.16
	Paris	0.48	1.25	0.03	2.83
Germany	Berlin	0.72	1.35	0.17	3.05
	Frankfurt	0.56	1.10	0.17	2.64
	Hamburg	0.40	1.79	0.22	2.90
	Dusseldorf	0.63	1.35	0.27	3.00
	Munich	0.73	1.08	0.27	2.67
	Ruhr	0.42	1.48	0.20	2.80
	Stuttgart	0.69	1.46	0.17	3.11
Greece	Athens	0.43	1.27	0.03	1.93

Country	Metropolitan area	Average Numbers of Daily Trips (Trips/Capita)			
		Public Modes	Private Modes	Mechanised Modes	Total
Italy	Milan	0.71	1.52	0.08	2.84
	Bologna	0.48	1.77	0.13	3.18
	Rome	0.63	1.53	0.08	2.70
	Turin	0.55	1.34	0.01	2.44
Netherlands	Amsterdam	0.66	1.20	0.90	3.83
Norway	Oslo	0.56	2.20	0.17	3.88
Portugal	Lisbon	n/a	n/a	n/a	n/a
Spain	Barcelona	0.40	0.89	0.01	1.84
	Madrid	0.62	0.59	0.00	1.95
Sweden	Stockholm	0.43	1.29	0.15	2.38
Switzerland	Berne	0.68	1.33	0.28	3.27
	Geneva	0.54	2.14	0.22	2.87
	Zurich	0.56	1.30	0.16	2.83
United Kingdom	Glasgow	0.33	1.55	0.02	2.83
	London	0.44	1.38	0.04	2.81
	Manchester	0.26	1.15	0.03	1.92
	Newcastle	0.49	1.29	0.05	2.67
Czech Republic	Prague	2.09	1.33	0.08	4.56
Hungary	Budapest	1.15	0.74	0.02	2.47
Poland	Cracow	0.85	0.37	0.03	1.75
	Warsaw	1.04	0.68	0.02	2.56
Turkey	Istanbul	1.28	0.89	n/a	n/a

n/a Not available

APPENDIX D: DATA ON AVERAGE TRIP DISTANCE

The transport data on average trip distance for the year 1995 were collected by the International Association of Public Transport (UITP) and Institute for Sustainability and Technology Policy (ISTP).

Country	Metropolitan area	Average trip distance (kilometres/trip)			
		Public modes	Private modes	Mechanised modes	Total
Austria	Graz	7.37	11.00	7.00	5.80
	Vienna	5.21	11.60	6.10	5.00
Belgium	Brussels	9.16	14.10	13.50	11.10
Denmark	Copenhagen	10.10	14.90	12.70	11.00
Finland	Helsinki	9.32	10.00	9.30	8.00
France	Lille	n/a	10.30	10.30	4.20
	Lyon	3.81	9.90	8.90	6.50
	Marseille	3.65	7.50	6.80	5.00
	Nantes	5.21	10.20	9.10	7.20
	Paris	10.16	11.30	10.90	6.90
Germany	Berlin	6.60	8.90	7.70	5.90
	Frankfurt	5.72	17.10	9.70	7.10
	Hamburg	9.96	12.50	10.70	9.10
	Dusseldorf	5.24	14.80	9.30	7.50
	Munich	9.85	15.00	10.90	8.80
	Ruhr	6.44	14.60	12.50	9.10
	Stuttgart	5.34	13.50	9.80	7.20
Greece	Athens	6.12	12.10	10.30	9.00

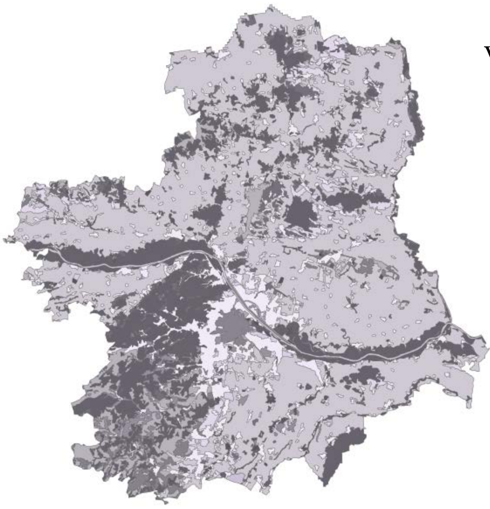
Country	Metropolitan area	Average Numbers of Daily Trips (Trips/Capita)			
		Public Modes	Private Modes	Mechanised Modes	Total
Italy	Milan	5.73	9.20	7.80	6.50
	Bologna	3.82	10.80	9.70	7.60
	Rome	16.62	13.20	14.20	11.50
	Turin	n/a	9.90	n/a	n/a
Netherlands	Amsterdam	4.72	12.70	6.10	6.00
Norway	Oslo	7.36	9.80	9.10	7.20
Portugal	Lisbon	n/a	n/a	n/a	n/a
Spain	Barcelona	10.01	10.30	7.00	5.50
	Madrid	6.47	22.80	13.80	8.80
Sweden	Stockholm	14.88	18.70	21.30	16.90
Switzerland	Berne	12.55	16.30	15.50	11.30
	Geneva	3.90	8.10	7.30	5.30
	Zurich	12.29	16.80	14.50	10.60
United Kingdom	Glasgow	7.26	13.70	12.50	9.50
	London	12.64	11.30	11.70	8.50
	Manchester	5.72	8.60	8.00	6.30
	Newcastle	6.57	12.50	10.80	7.60
Czech Republic	Prague	5.67	9.20	9.80	7.70
Hungary	Budapest	8.61	11.90	6.20	4.90
Poland	Cracow	5.71	9.90	8.40	6.30
	Warsaw	n/a	14.00	6.70	5.00
Turkey	Istanbul	n/a	13.80	11.40	8.20

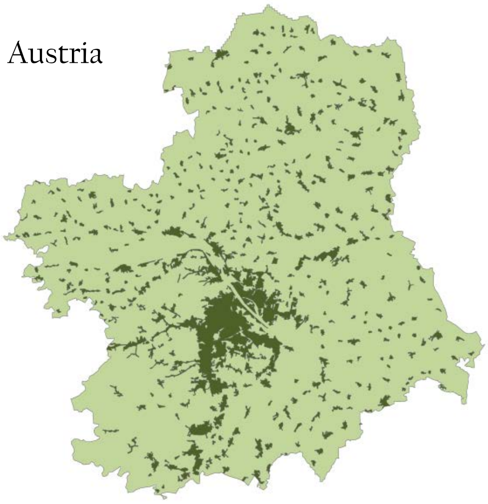
n/a Not available

APPENDIX E LAND COVER MAPS OF 30 EUROPEAN AREAS

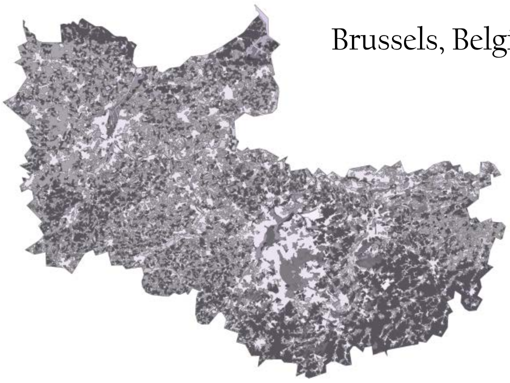
From the European metropolitan areas listed by the Organisation for Economic Cooperation and Development (OECD) and their units included in defining each metro-region area shown in Appendix A, land cover maps, at 250-metre resolution for thirty of these metropolitan areas were obtained from the CORINE land cover 2000 data set. This is produced by the European Commission programme of the COoRdination of INformation on the Environment (CORINE) pioneered by the European Environment Agency (EEA). These maps will be presented as we ordered them previously in Table 5.1. Merging maps of contiguous residential polygons defining these land covers, residential land-use maps (below right) are also displayed next to the land cover map (below left) of each metropolitan area. Different shades of colour are used in distinguishing the 44 land-use classes categorised by CORINE, and in the case of residential land-use maps, polygons with a dark green colour refer to residential land use, while the light green colour is used to represent non-residential land use polygons. It should be noted that these maps are not presented to scale, in other words it is not possible to compare their areal extent on the printed page.

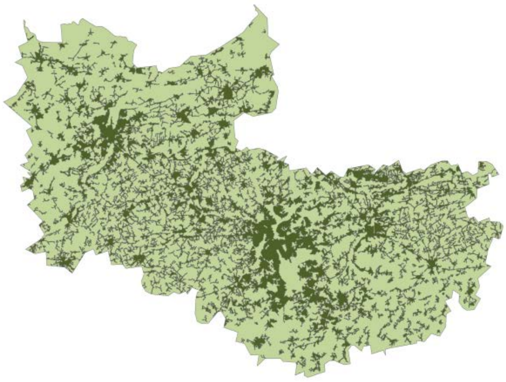
Vienna, Austria



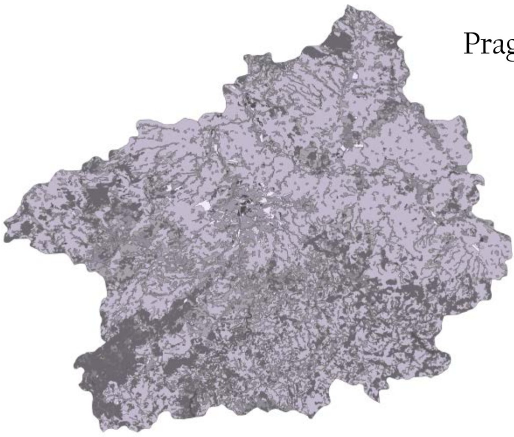


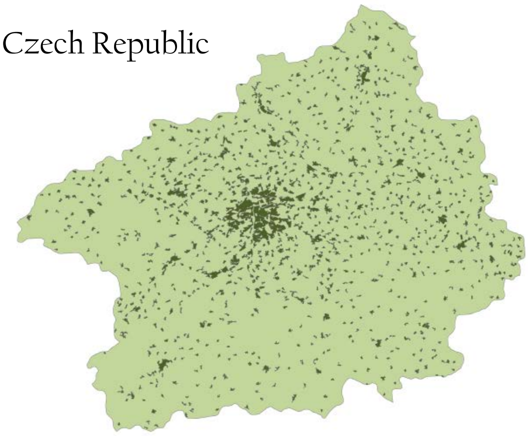
Brussels, Belgium

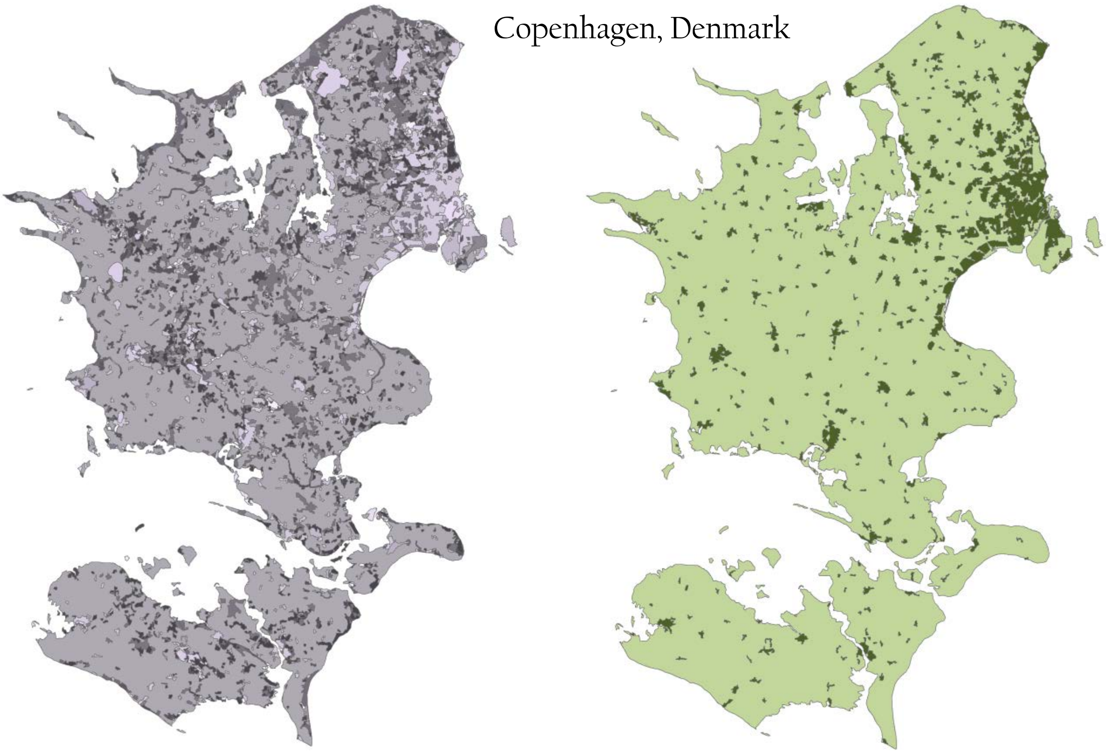


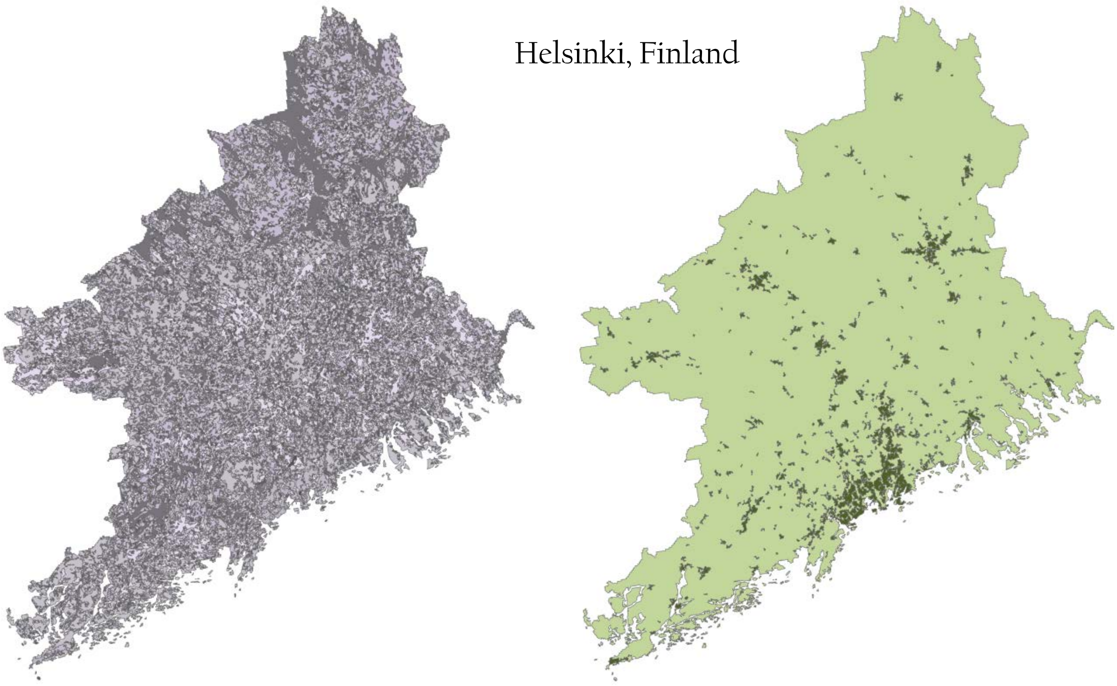


Prague, Czech Republic

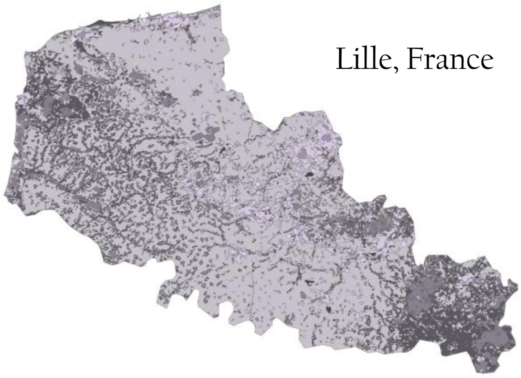


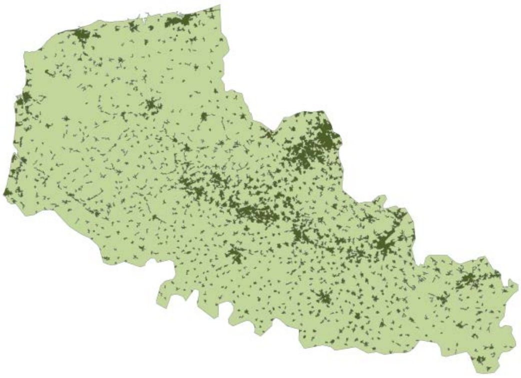



Copenhagen, Denmark

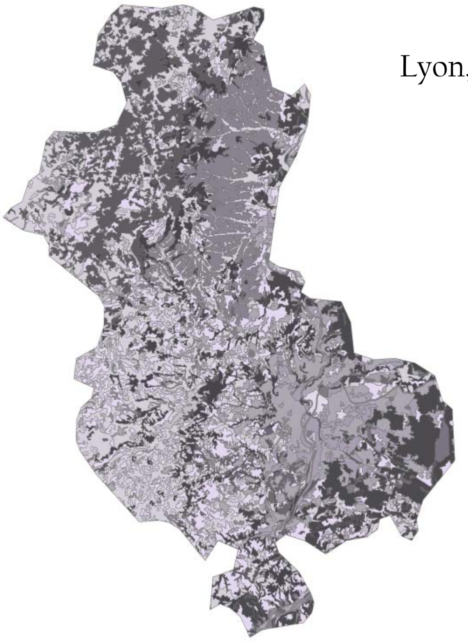

Helsinki, Finland

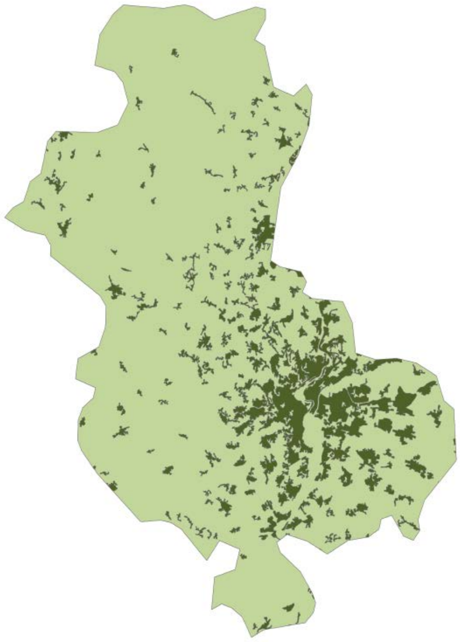
Lille, France



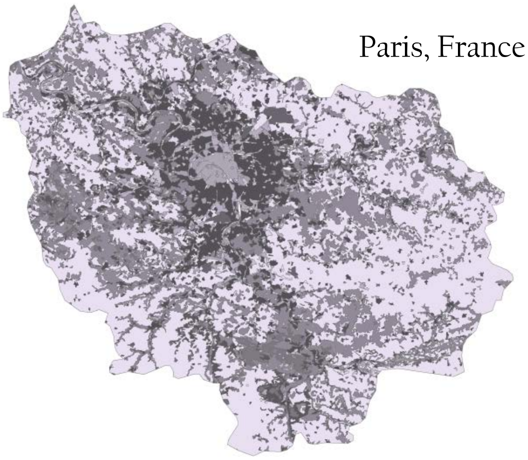


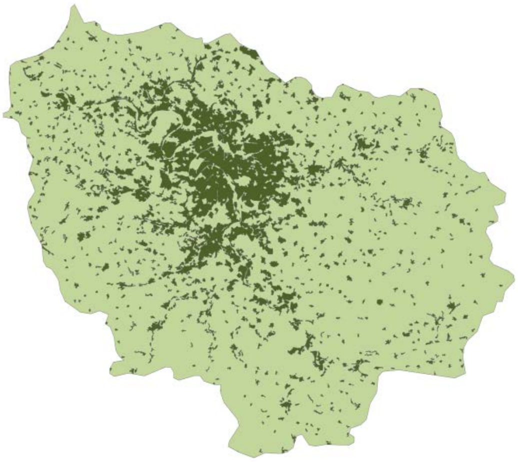
Lyon, France

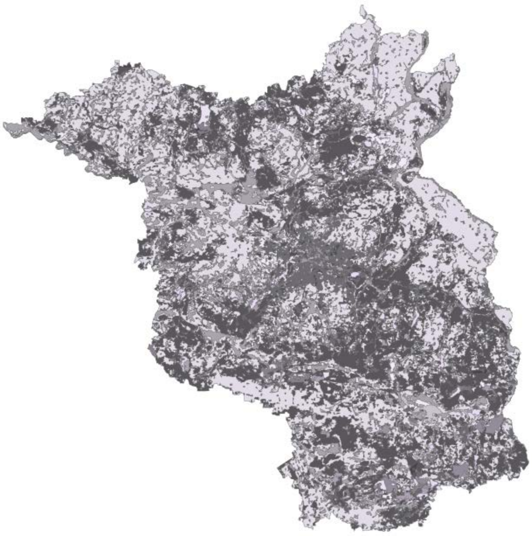




Paris, France

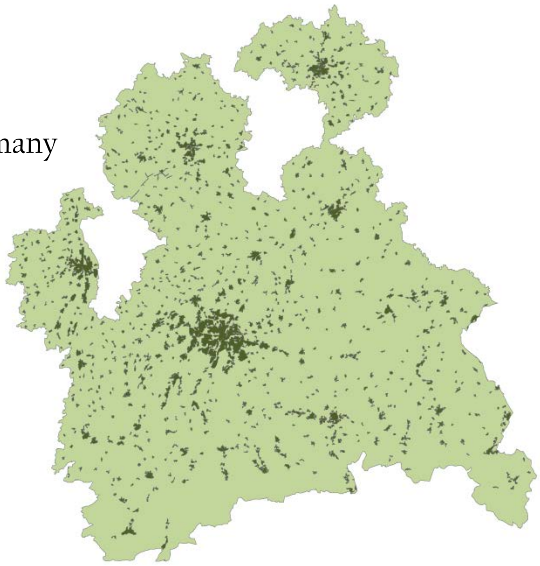


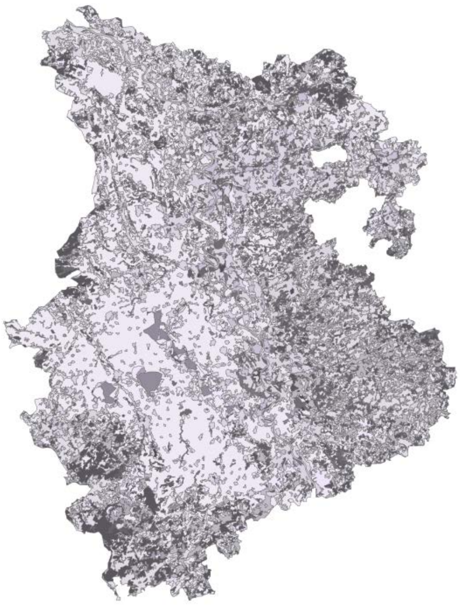




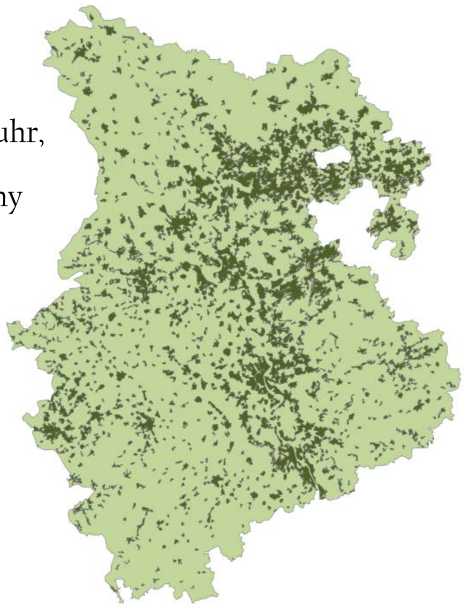
Berlin, Germany

Munich, Germany

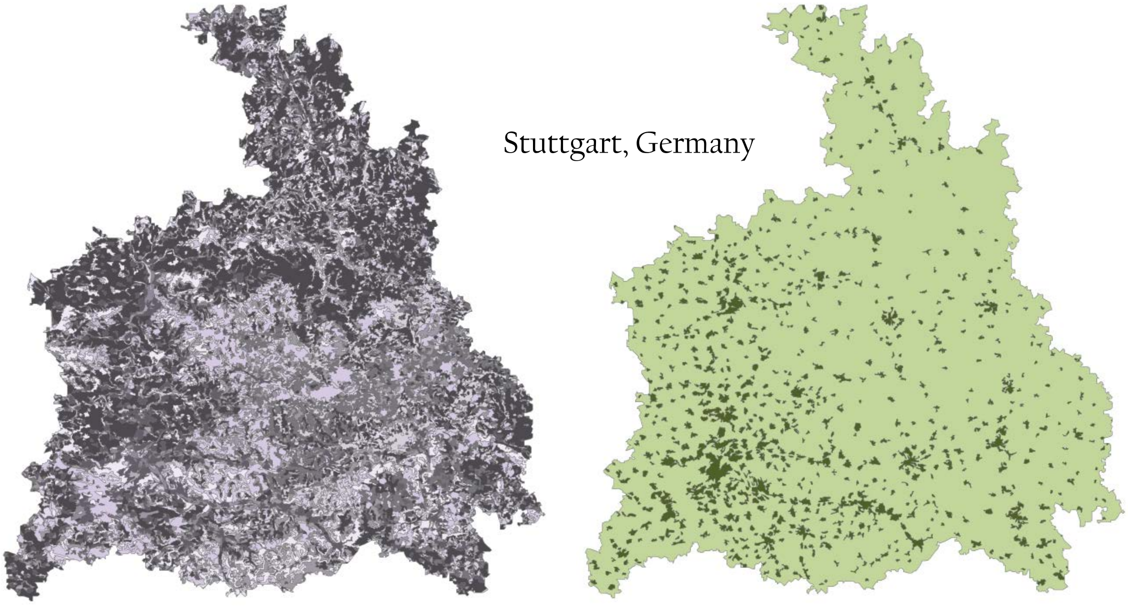




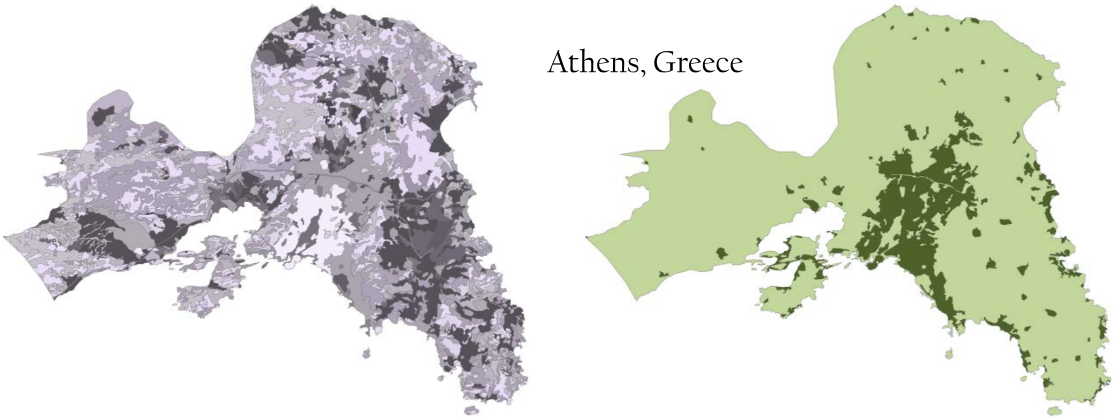
Rhein-Ruhr, Germany



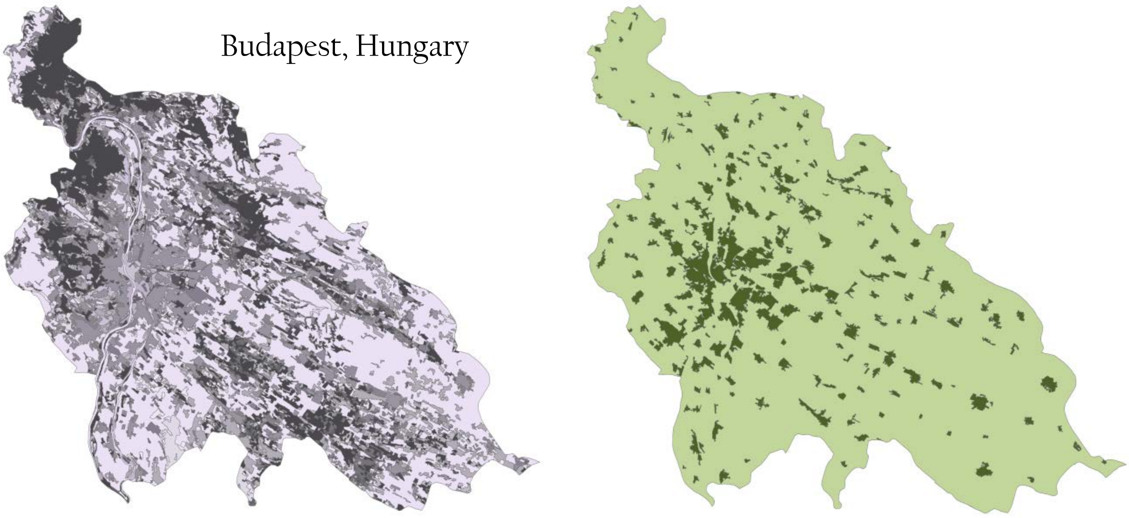
Stuttgart, Germany

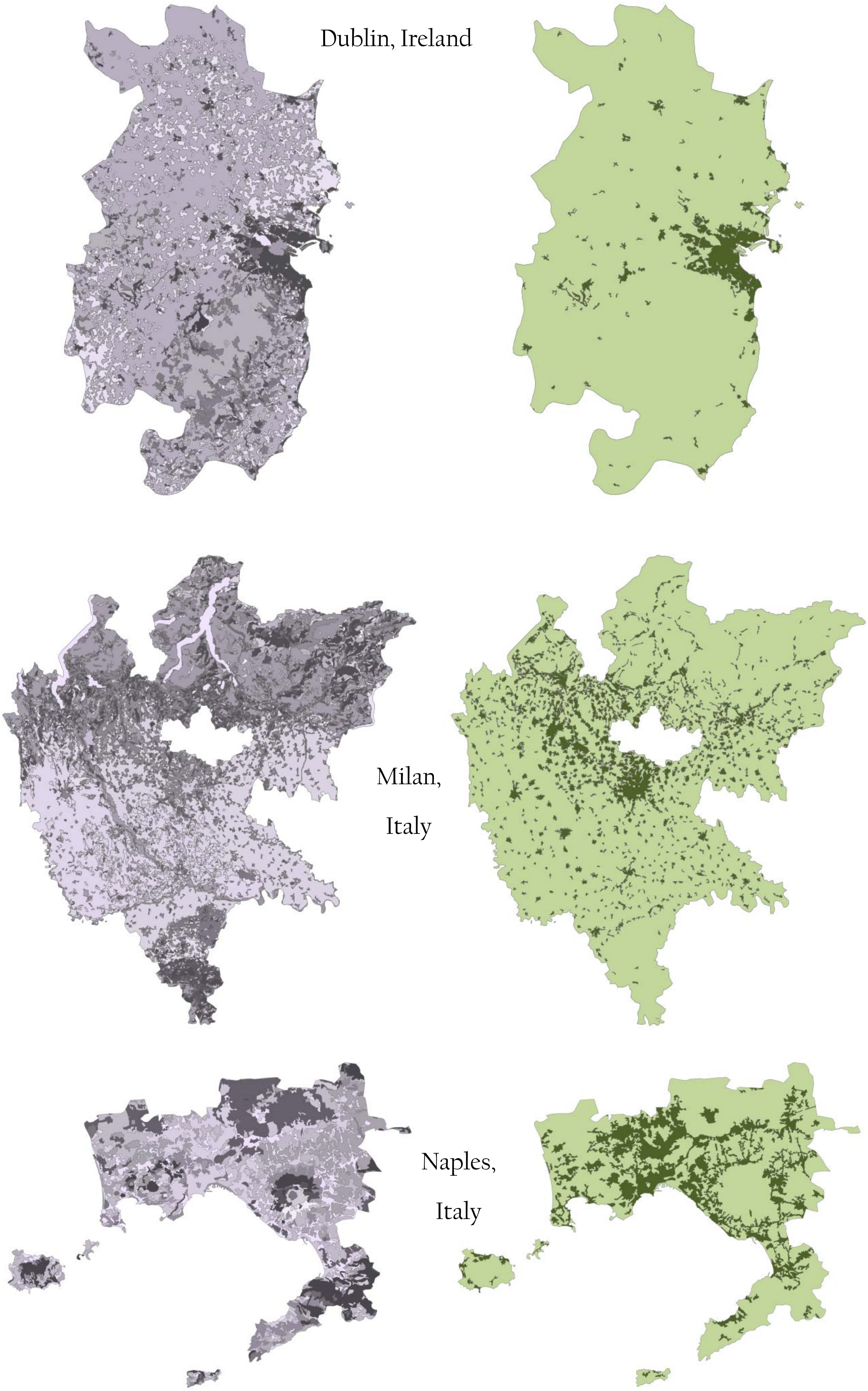


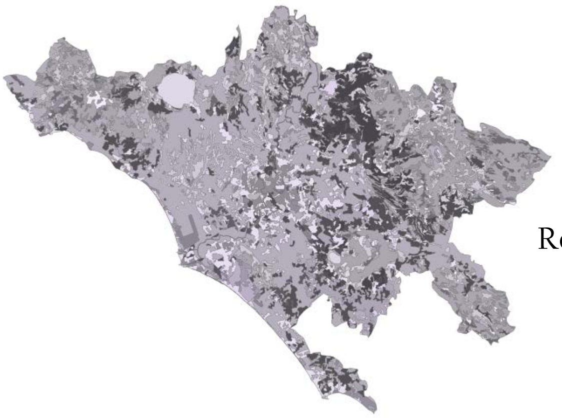
Athens, Greece



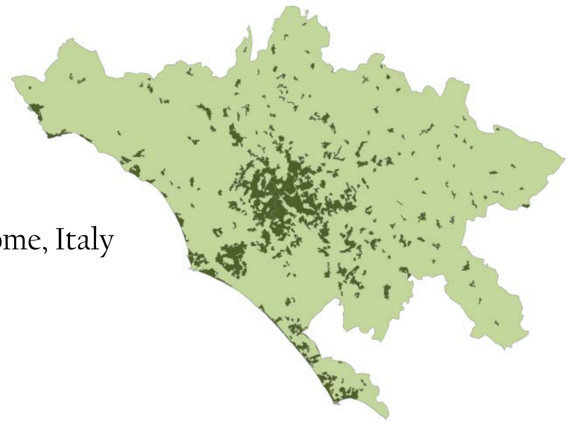
Budapest, Hungary

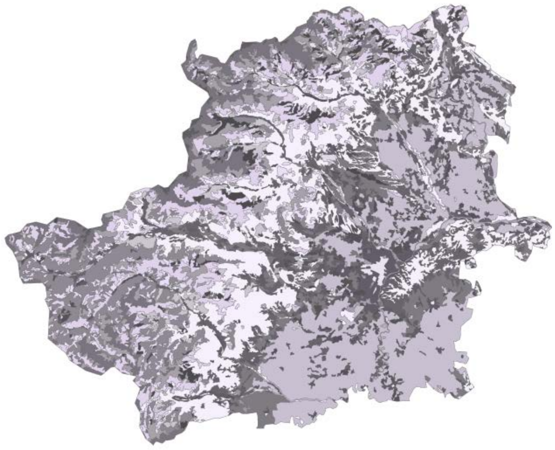



Dublin, Ireland
Milan,
Italy
Naples,
Italy

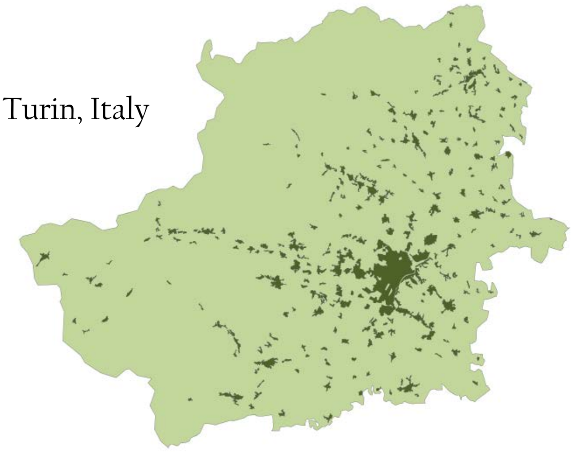


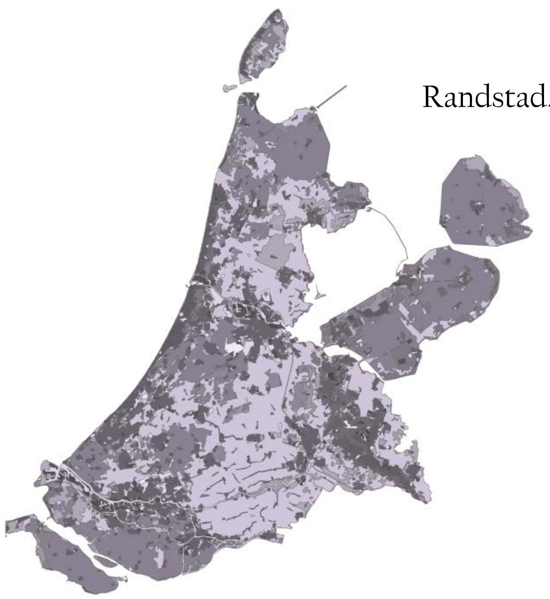
Rome, Italy



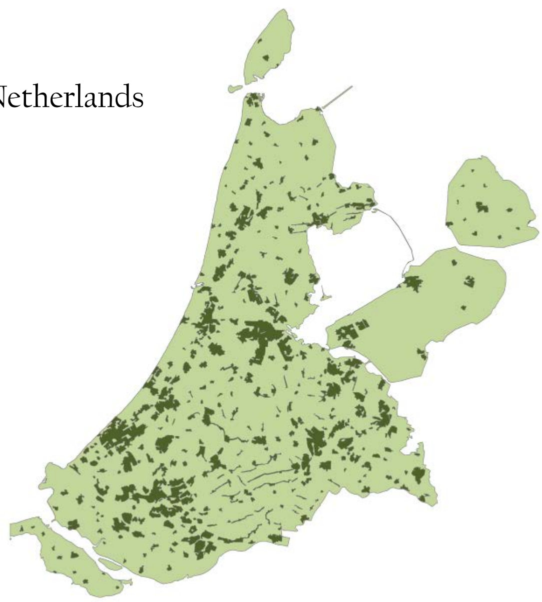


Turin, Italy

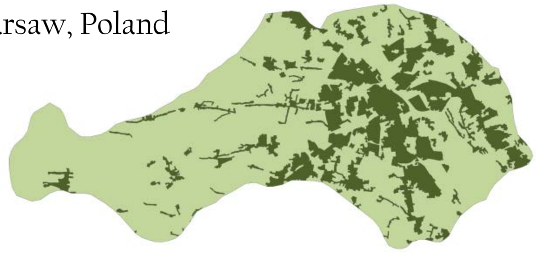




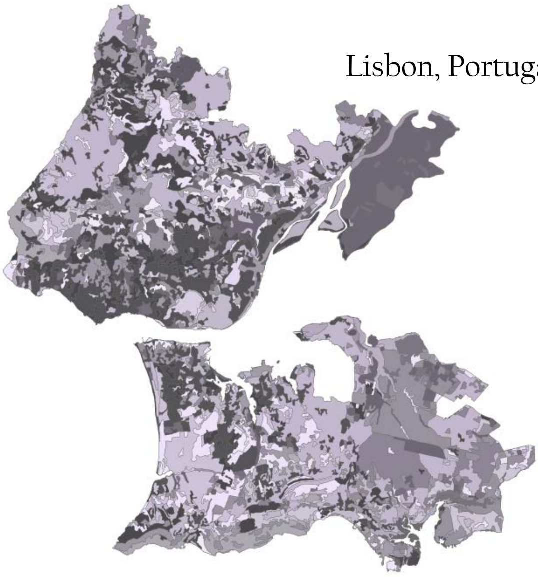
Randstad, Netherlands

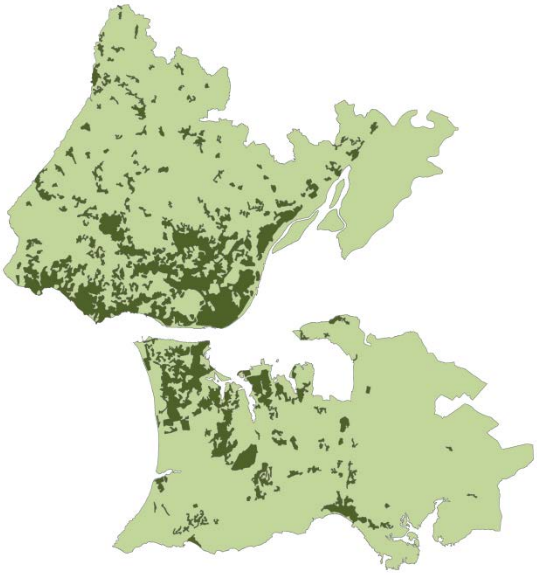


Warsaw, Poland

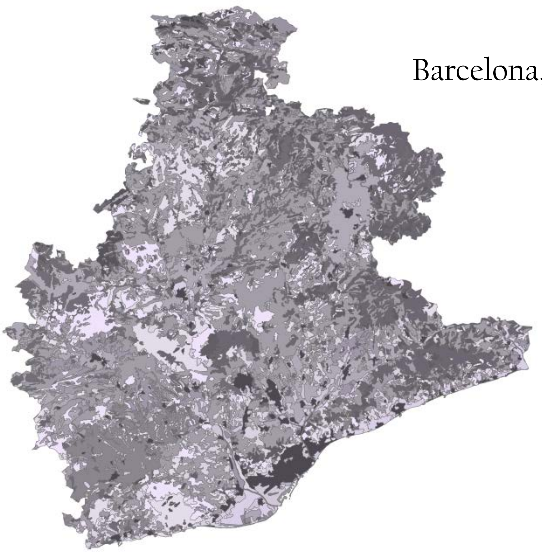


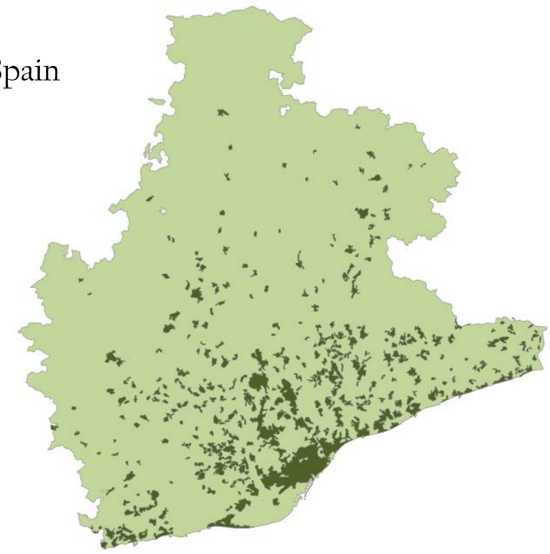
Lisbon, Portugal

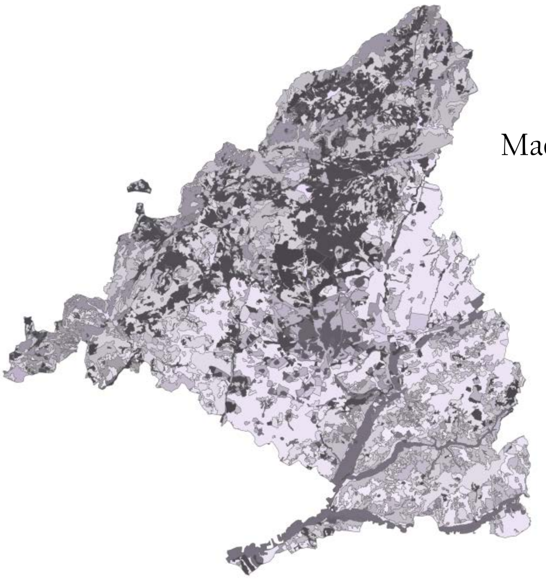




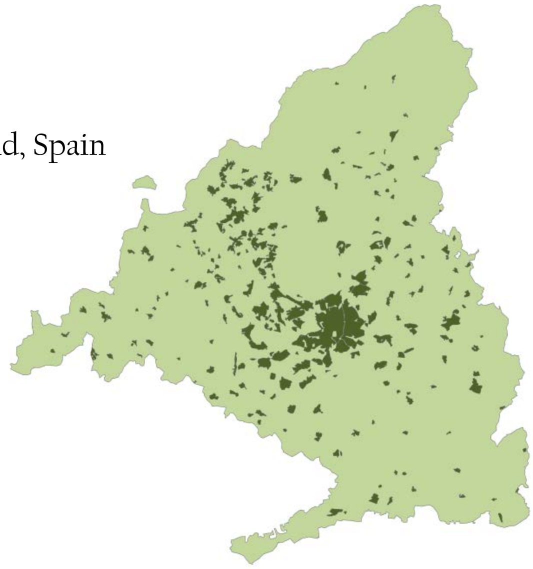
Barcelona, Spain

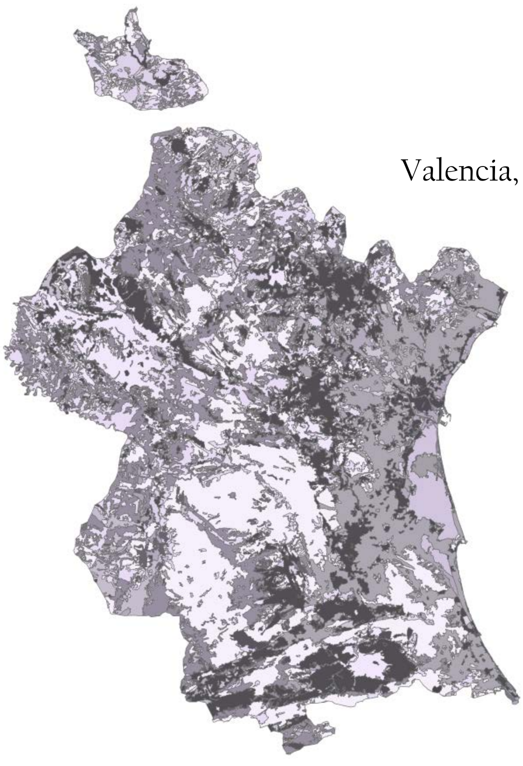




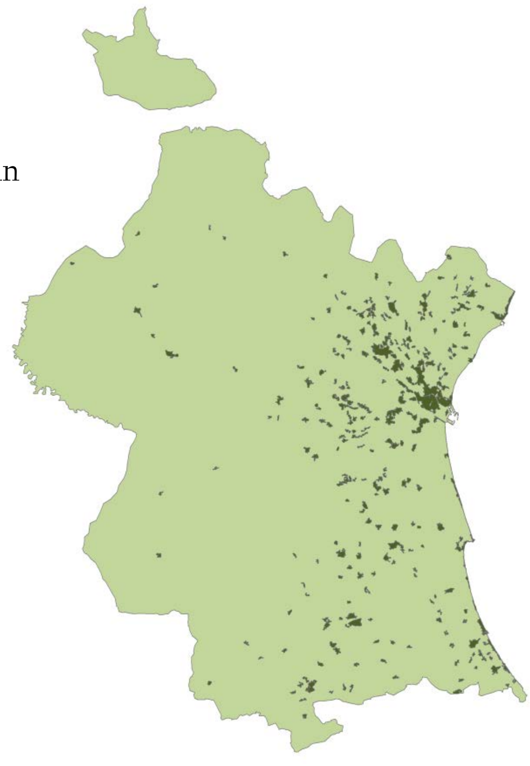


Madrid, Spain



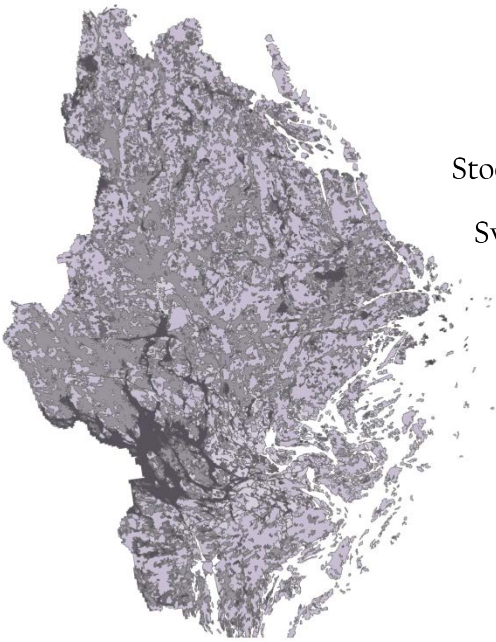


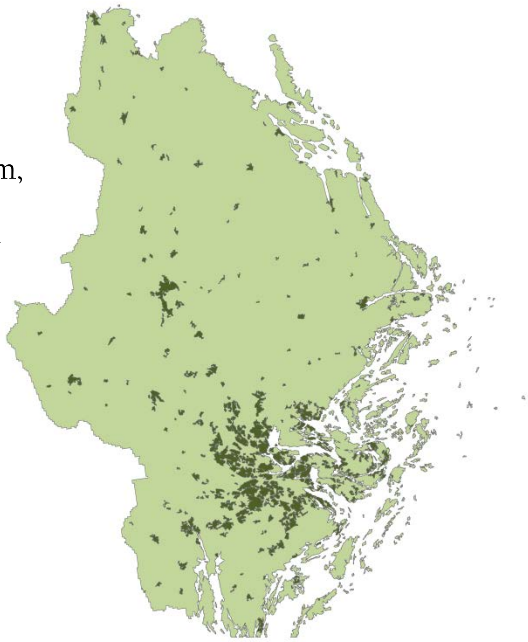
Valencia, Spain



Stockholm,

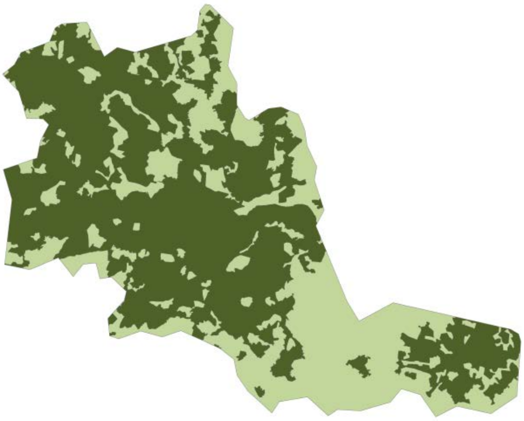
Sweden



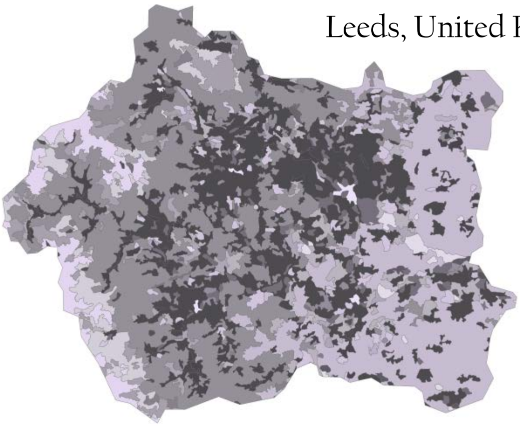


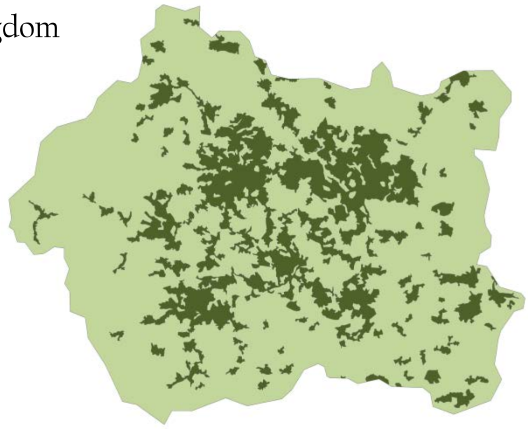
Birmingham,

United Kingdom



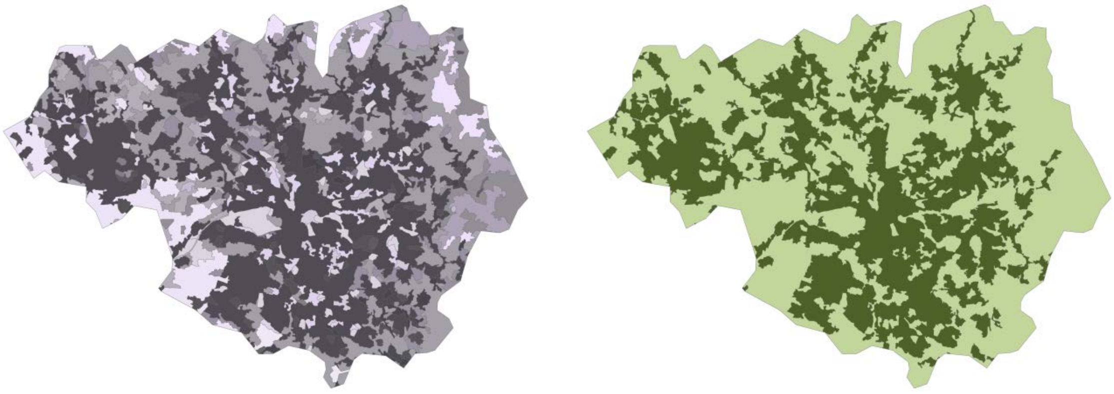
Leeds, United Kingdom





London, United Kingdom

Manchester, United Kingdom



APPENDIX F: THE CALCULATED FDS, ACL, ACO AND RCO INDICES

For thirty EU metropolitan areas, the calculated FDS, ACL, ACO and RCO exceed their theoretical ranges, shown in parentheses under each indicator; consequently, they are eliminated from the analysis of modelling sprawl.

Operational dimension of sprawl		Complexity
Country	**Metropolitan area**	**FDS (+1 to +2)**
Austria	Vienna	0.00490076
Belgium	Brussels	0.012437810
Denmark	Copenhagen	0.00441306
Finland	Helsinki	0.00688942
France	Lille	0.00623441
	Lyon	0.00788644
	Paris	0.00391389
Germany	Berlin	0.00387522
	Munich	0.00502765
	Rhein-Ruhr	0.00631712
	Stuttgart	0.00741840
Greece	Athens	0.00308690
Italy	Milan	0.00631912
	Rome	0.00509295
	Turin	0.00397535
	Naples	0.00819336
Netherlands	Randstad	0.00400641
Portugal	Lisbon	0.00573888
Spain	Barcelona	0.00403714
	Madrid	0.00344887
	Valencia	0.00709220
Sweden	Stockholm	0.00606612
United Kingdom	London	0.00348250
	Manchester	0.00478813
	Leeds	0.00526316
	Birmingham	0.00256772
Ireland	Dublin	0.00313529
Czech Republic	Prague	0.00713012
Hungary	Budapest	0.00502639
Poland	Warsaw	0.00568666

Conceptual dimension of sprawl		2.2) Clustering			
Operational dimension of sprawl		2.2.3) Absolute Clustering Index (ACL) (0 to +1)			
		Size of tessellated grid			
Country	Metropolitan area	1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2
Austria	Vienna	0.93209	0.061116	0.052322	0.043752	0.029349
Belgium	Brussels	0.88522	0.027471	0.030793	0.030380	0.030787
Denmark	Copenhagen	0.77668	0.016608	0.013718	0.008611	0.007240
Finland	Helsinki	0.84467	0.027015	0.028920	0.029629	0.029206
France	Lille	0.84911	0.021633	0.022033	0.023659	0.024806
	Lyon	0.80289	0.017861	0.014466	0.005318	-0.007680
	Paris	0.80154	0.043112	0.044254	0.044748	0.043487
Germany	Berlin	n/a	0.072434	0.072403	0.075063	0.072270
	Munich	0.87299	0.029594	0.029175	0.027560	0.027453
	Rhein-Ruhr	0.79368	0.019005	0.022498	0.025275	0.026710
	Stuttgart	0.89069	0.032426	0.036875	0.036360	0.039822
Greece	Athens	0.85686	0.021851	0.011551	-0.003190	-0.018000
Italy	Milan	0.86134	0.041746	0.047286	0.046814	0.045147
	Rome	0.87280	0.027435	0.025751	0.016786	0.004970
	Turin	0.86689	0.023093	0.014203	0.009521	0.0000996
	Naples	0.92508	0.019562	-0.00057	-0.020610	-0.055450
Netherlands	Randstad	0.78644	0.007779	0.009653	0.0110180	0.0133970
Portugal	Lisbon	0.82452	0.012403	0.005668	0.000473	-0.012540
Spain	Barcelona	0.87978	0.021306	0.016922	0.018471	0.012048
	Madrid	0.87614	0.031171	0.027163	0.021566	0.0156610
	Valencia	0.86149	0.017629	0.008849	0.007118	0.0017590
Sweden	Stockholm	0.83958	0.045426	0.050218	0.048695	0.049444
United Kingdom	London	0.83034	0.044170	0.051381	0.052227	0.053769
	Manchester	0.82818	0.001805	-0.00266	-0.012840	-0.027720
	Leeds	0.81019	0.004525	0.001670	-0.008140	-0.017640
	Birmingham	0.84337	0.004102	-0.00472	-0.019630	-0.041960
Ireland	Dublin	0.80361	0.026782	0.014010	0.006571	-0.014700
Czech Republic	Prague	0.83160	0.026053	0.027510	0.028093	0.027973
Hungary	Budapest	0.80527	0.016724	0.019015	0.018015	0.018130
Poland	Warsaw	0.72416	0.00149	-0.004110	-0.015930	-0.023260

n/a Not available

Conceptual dimension of sprawl		3.2) Concentration				
Operational dimension of sprawl		3.2.2) Absolute Concentration Index (ACO) (0 to +1)				
		Size of tessellated grid				
Country	Metropolitan area	1x1 km²	2x2 km²	3x3 km²	4x4 km²	5x5 km²
Austria	Vienna	0.70	0.71	0.71	0.74	0.78
Belgium	Brussels	0.74	0.75	0.79	0.79	0.80
Denmark	Copenhagen	0.54	0.43	0.40	0.40	0.42
Finland	Helsinki	0.68	0.66	0.64	0.61	0.60
France	Lille	-1.83	-0.51	-0.55	-0.58	-0.57
	Lyon	-3.39	-1.91	-2.03	-2.43	-2.19
	Paris	-0.78	-0.55	-0.43	-0.57	-0.65
Germany	Berlin	0.77	0.73	0.70	0.68	0.69
	Munich	-0.56	-0.92	-1.46	-1.92	-2.71
	Rhein-Ruhr	-0.76	-0.75	-1.11	-1.56	-1.87
	Stuttgart	-0.39	-0.60	-1.27	-1.46	-1.54
Greece	Athens	-0.66	-0.93	-1.68	-2.14	-2.53
Italy	Milan	-1.18	-1.61	-3.41	-5.55	-8.20
	Rome	-1.11	-1.27	-1.84	-2.64	-3.64
	Turin	-1.03	-1.05	-1.67	-2.61	-3.18
	Naples	-1.19	-1.23	-1.79	-2.83	-3.66
Netherlands	Randstad	-1.24	-1.57	-4.07	-30.94	12.95
Portugal	Lisbon	-1.83	-2.12	-4.59	-10.51	81.80
Spain	Barcelona	-0.54	-0.73	-1.31	-2.06	-2.84
	Madrid	-0.83	-1.02	-1.39	-2.27	-3.21
	Valencia	-0.46	-0.66	-1.01	-1.38	-1.59
Sweden	Stockholm	-0.54	-1.00	-1.56	-2.02	-2.67
United Kingdom	London	-0.76	-1.03	-1.98	-2.96	-4.11
	Manchester	-2.61	-3.28	-5.27	-7.36	-11.37
	Leeds	-2.57	-3.29	-5.29	-8.00	-19.90
	Birmingham	-2.49	-3.10	-4.61	-5.73	-9.08
Ireland	Dublin	-1.95	-1.99	-2.88	-3.11	-2.53
Czech Republic	Prague	-0.61	-0.32	-0.58	-0.80	-1.05
Hungary	Budapest	-0.65	-0.37	-0.65	-0.89	-1.10
Poland	Warsaw	-0.86	-0.56	-0.85	-1.07	-1.48

Conceptual dimension of sprawl		3.2) Concentration				
Operational dimension of sprawl		3.2.3) Relative Concentration Index (RCO) (-1 to +1)				
		Size of tessellated grid				
Country	Metropolitan area	1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2
Austria	Vienna	1.07	1.07	1.07	1.06	1.05
Belgium	Brussels	1.06	1.07	1.07	1.07	1.07
Denmark	Copenhagen	1.28	1.39	1.49	1.53	1.55
Finland	Helsinki	1.11	1.15	1.16	1.18	1.18
France	Lille	0.88	0.76	0.77	0.78	0.79
	Lyon	0.84	0.73	0.74	0.78	0.76
	Paris	0.75	0.72	0.66	0.72	0.72
Germany	Berlin	1.05	1.06	1.07	1.07	1.06
	Munich	0.68	0.74	0.79	0.82	0.86
	Rhein-Ruhr	0.73	0.73	0.77	0.81	0.84
	Stuttgart	0.41	0.49	0.65	0.67	0.68
Greece	Athens	0.45	0.53	0.66	0.72	0.74
Italy	Milan	0.71	0.75	0.85	0.89	0.91
	Rome	0.59	0.62	0.69	0.76	0.82
	Turin	0.55	0.55	0.66	0.74	0.77
	Naples	0.59	0.60	0.68	0.78	0.84
Netherlands	Randstad	0.74	0.78	0.93	1.04	1.11
Portugal	Lisbon	0.72	0.76	0.90	0.98	1.06
Spain	Barcelona	0.45	0.51	0.65	0.75	0.81
	Madrid	0.52	0.57	0.63	0.73	0.79
	Valencia	0.37	0.46	0.58	0.63	0.67
Sweden	Stockholm	0.51	0.62	0.70	0.74	0.78
United Kingdom	London	0.76	0.8	0.87	0.90	0.93
	Manchester	0.75	0.8	0.87	0.91	0.93
	Leeds	0.75	0.8	0.87	0.92	0.96
	Birmingham	0.75	0.79	0.86	0.90	0.93
Ireland	Dublin	0.70	0.71	0.78	0.77	0.74
Czech Republic	Prague	0.47	0.35	0.46	0.52	0.58
Hungary	Budapest	0.48	0.37	0.48	0.55	0.59
Poland	Warsaw	0.50	0.38	0.47	0.52	0.58

APPENDIX G: THE CALCULATED ALD, PAR, FDB, MORAN AND GC′ INDICES

It is not possible to test the ALD's, PAR's, FDB's, MORAN's and GC's structures for their level of stability; however, their calculated degrees for thirty EU metropolitan areas are fed into the model of sprawl.

Operational dimension of sprawl		Average density	Complexity		Clustering	
Country	Metropolitan area	ALD	PAR	FDB	MORAN	GC′
Austria	Vienna	0.10580154	0.00481700	1.8251	-0.00206980	-0.0060970
Belgium	Brussels	0.25193896	0.00771461	1.8822	-0.00235570	-0.0063828
Denmark	Copenhagen	0.07936014	0.00420887	1.8672	-0.00214850	-0.00092437
Finland	Helsinki	0.04514205	0.00613888	1.8507	-0.00190210	-0.0108430
France	Lille	0.10205936	0.00682698	1.8462	-0.00076217	-0.0051434
	Lyon	0.117110170	0.00633607	1.8545	-0.00391010	-0.0047008
	Paris	0.14967813	0.00403549	1.8141	-0.00099538	-0.0127390
Germany	Berlin	0.06199842	0.00524876	1.8465	-0.00055380	-0.0238850
	Munich	0.05845873	0.00562415	1.8258	-0.00083436	-0.0135750
	Rhein-Ruhr	0.17140203	0.00465305	1.8263	-0.00073716	-0.0011553
	Stuttgart	0.07973291	0.00567199	1.8436	-0.00072089	-0.0041692
Greece	Athens	0.12993251	0.00259113	1.9102	-0.01036900	-0.0081849
Italy	Milan	0.11212978	0.00578287	1.8471	-0.00084225	-0.0113650
	Rome	0.09413596	0.00431315	1.8915	-0.00263360	-0.0049425
	Turin	0.05449001	0.00553634	1.7961	-0.00332830	-0.0079525
	Naples	0.24982569	0.00562320	1.9397	-0.00624210	-0.0041447
Netherlands	Randstad	0.13753202	0.00322602	1.9296	-0.00256830	-0.0057259
Portugal	Lisbon	0.15534691	0.00440476	1.8901	-0.00443120	-0.0053268
Spain	Barcelona	0.07657186	0.00447380	1.8553	-0.00217760	-0.0048268
	Madrid	0.06902312	0.00325996	1.8773	-0.0029896	-0.0088244
	Valencia	0.02451488	0.00648978	1.8012	-0.0033077	-0.0069467
Sweden	Stockholm	0.05278622	0.00477786	1.8504	-0.0027584	-0.0095213
United Kingdom	London	0.17061629	0.00300869	1.8873	-0.00153110	-0.0166240
	Manchester	0.41962089	0.00265211	1.9079	-0.0206310	-0.0054335
	Leeds	0.22602430	0.00356900	1.8419	-0.0010122	-0.0034526
	Birmingham	0.61384476	0.00151609	1.9537	-0.0561300	-0.0043663
Ireland	Dublin	0.05418935	0.00359624	1.7557	-0.0079470	-0.0073937
Czech Republic	Prague	0.06240465	0.0074859	1.7834	-0.00081252	-0.0105660
Hungary	Budapest	0.10057353	0.00389304	1.8583	-0.00416430	-0.0084209
Poland	Warsaw	0.24013180	0.00436754	1.8869	-0.01097900	-0.0015169

APPENDIX H: THE CALCULATED DEGREE OF INDICATORS IN STABILITY TESTS

For thirty metropolitan areas in seventeen countries, sixteen operational dimensions of sprawl are calculated by applying five different grid sizes in the analysis and these are presented in individual table. The numbers displayed in front of each conceptual and operational dimension of sprawl link to the ones summarised in Table 4.8. The amount of pair-data violating its pattern of changing-degree (**Ω**) of each metropolitan area is presented on the rightmost column, while the total amount of **Ω** of each indicator is summarised, in the same column, at the bottom of the table. Details of how to count for **Ω** are described in Figure 6.14. For the most suitable grid size in estimating each indicator, numbers of pair-data disagreeing with the pattern of changing-degree of its entire dataset (Θ_{12}, Θ_{23}, Θ_{34} and Θ_{45}), Θ_2, Θ_3 and Θ_4 are presented at the bottom of the table.

In estimating the degree of ISP for the case of Berlin, and the degree of RCL for the case of Berlin and Rhein-Ruhr, applying grid size of 1x1 km^2 creates too many sub-areas to work with and causes error in the calculation; however, those errors do not affect the decision-making in selecting the optimal grid size.

Conceptual dimension of sprawl	**1.2) Density Gradient**
Operational dimension of sprawl	**1.2.1) Density Gradient: Inverse Power Function (DGI)**

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Higher**

Country	**Metropolitan area**	**Size of tessellated grid**					**Ω**
		1x1 km^2	**2x2 km^2**	**3x3 km^2**	**4x4 km^2**	**5x5 km^2**	
Austria	Vienna	0.352500	0.511800	0.60870	0.618500	0.65540	0
Belgium	Brussels	0.080880	0.06046	0.09692	0.116100	0.10600	2
Denmark	Copenhagen	-0.295500	-0.64840	-0.64770	0.03989	0.04465	2
Finland	Helsinki	-2.337000	-2.77300	-0.05777	-3.07000	-0.15050	5
France	Lille	0.152200	0.26840	0.33450	0.34000	0.34960	0
	Lyon	0.271200	0.38070	0.43480	0.30060	0.34680	4
	Paris	0.308300	0.43260	0.477100	0.53020	0.51490	1
Germany	Berlin	0.3121000	0.48230	0.55890	0.59040	0.66830	0
	Munich	0.021840	0.22020	0.22700	0.26370	0.35610	0
	Rhein-Ruhr	0.099560	0.15200	0.210100	0.23720	0.23000	1
	Stuttgart	-0.428200	0.03465	-0.011100	0.09895	0.07040	2
Greece	Athens	0.123500	0.24220	0.28260	0.33260	0.41070	0
Italy	Milan	-0.463500	-0.26180	0.35960	0.31160	0.3445	2
	Rome	0.1777000	0.36360	0.45230	0.55500	0.65070	0
	Turin	0.144400	0.26630	0.29260	0.45220	0.47500	0
	Naples	0.126300	0.18620	0.24960	0.20980	0.25020	1
Netherlands	Randstad	-1.544000	-0.6495	-1.62100	-0.37620	-0.30120	2
Portugal	Lisbon	-0.033180	-0.5426	0.30270	0.38460	0.42760	1
Spain	Barcelona	-0.215800	0.21980	0.31000	0.301700	0.28600	3
	Madrid	0.157500	0.26750	0.32040	0.431300	0.40160	1
	Valencia	0.020040	0.09296	0.09908	0.076730	0.119700	2
Sweden	Stockholm	0.134000	0.15230	0.26820	0.332100	0.39520	0
United Kingdom	London	0.268200	0.3948	0.42170	0.514200	0.52220	0
	Manchester	0.070350	0.11340	0.116700	0.126900	0.116600	2
	Leeds	0.004168	0.06877	0.115200	0.08243	0.27800	1
	Birmingham	0.099800	0.13450	0.14580	0.153000	0.16580	0
Ireland	Dublin	0.057230	0.13050	0.35890	0.450100	0.42670	1
Czech Republic	Prague	0.285300	0.46360	0.47330	0.539800	0.58210	0
Hungary	Budapest	-0.157200	0.21930	0.37550	0.370500	0.39230	1
Poland	Warsaw	0.235500	0.32300	0.34220	0.295600	0.28660	5
		Θ_{12} = 4	Θ_{23} = 2	Θ_{34} = 9	Θ_{45} = 9		Total Ω = 39
			Θ_2 = 6	Θ_3 = 11	Θ_4 = 18		

Conceptual dimension of sprawl	1.2) Density Gradient
Operational dimension of sprawl	**1.2.2) Density Gradient: Negative Exponential Function (DGN)**

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Higher**

Country	Metropolitan area	Size of tessellated grid					Ω
		1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	
Austria	Vienna	0.00002251	0.00003558	0.00004243	0.00004256	0.00004341	0
Belgium	Brussels	0.00000427	0.00000553	0.00000652	0.00000664	0.00000640	2
Denmark	Copenhagen	0.00000094	0.00000168	0.00000274	0.00000417	0.00000450	0
Finland	Helsinki	-0.00000031	-0.00000006	0.00000195	0.00000154	0.00000311	1
France	Lille	0.00000504	0.00000849	0.00001048	0.00001158	0.00001145	1
	Lyon	0.00001937	0.00003120	0.00003557	0.00003566	0.00003382	2
	Paris	0.00001368	0.00002047	0.00002395	0.00002502	0.00002595	0
Germany	Berlin	0.00000745	0.00001390	0.00001814	0.00002153	0.00002292	0
	Munich	0.00000424	0.00000637	0.00000738	0.00000859	0.00001041	0
	Rhein-Ruhr	0.00000382	0.00000602	0.00000746	0.00000868	0.00000869	0
	Stuttgart	0.00000042	0.00000221	0.00000278	0.00000414	0.00000500	0
Greece	Athens	0.00001008	0.00001970	0.00002915	0.00003064	0.00003371	0
Italy	Milan	0.00000746	0.00001231	0.00001550	0.00001651	0.00001757	0
	Rome	0.00001586	0.00002864	0.00003427	0.00003998	0.00004293	0
	Turin	0.00001497	0.00002126	0.00002612	0.00003056	0.00003242	0
	Naples	0.00001075	0.00001456	0.00001858	0.00001652	0.00002019	1
Netherlands	Randstad	-0.00000189	-0.0000020	-0.00000270	-0.00000155	0.00000079	3
Portugal	Lisbon	0.00001466	0.00002307	0.00002896	0.00003237	0.00003511	0
Spain	Barcelona	0.00000603	0.00001047	0.00001292	0.00001599	0.00001775	0
	Madrid	0.00001082	0.00001892	0.00002546	0.00002890	0.00002832	1
	Valencia	0.00000298	0.00000453	0.00000551	0.00000535	0.00000785	1
Sweden	Stockholm	0.00000324	0.00000546	0.00000814	0.00000905	0.00001188	0
United Kingdom	London	0.00000796	0.00001337	0.00001628	0.00001795	0.00001915	0
	Manchester	0.00000837	0.00001333	0.00001334	0.00001615	0.00001462	1
	Leeds	0.00000465	0.00001524	0.00002012	0.00001986	0.00003120	1
	Birmingham	0.00000875	0.00001051	0.00001154	0.00001123	0.00001335	1
Ireland	Dublin	0.00000859	0.00001532	0.00002311	0.00002792	0.00003353	0
Czech Republic	Prague	0.00001197	0.00002113	0.00002557	0.00002699	0.00002938	0
Hungary	Budapest	0.00000551	0.00001001	0.00001672	0.00001812	0.00001877	0
Poland	Warsaw	0.00002358	0.00003172	0.00003447	0.00002854	0.00002649	5
		Θ_{12} = 1	Θ_{23} = 1	Θ_{34} = 6	Θ_{45} = 6		Total Ω = 20
			Θ_2 = 1	Θ_3 = 7	Θ_4 = 12		

Conceptual dimension of sprawl	**2.2) Clustering**
Operational dimension of sprawl	**2.2.4) Index of Spatial Proximity (ISP)**

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Lower**

Country	**Metropolitan area**	**Size of tessellated grid**					**Ω**
		1x1 km^2	**2x2 km^2**	**3x3 km^2**	**4x4 km^2**	**5x5 km^2**	
Austria	Vienna	0.99980	0.99923	0.99878	0.99823	0.99787	0
Belgium	Brussels	0.99988	0.99965	0.99942	0.99925	0.99916	0
Denmark	Copenhagen	0.99992	0.99948	0.99914	0.99900	0.99890	0
Finland	Helsinki	0.99992	0.99964	0.99932	0.99901	0.99903	1
France	Lille	0.99992	0.99973	0.99955	0.99948	0.99920	0
	Lyon	0.99957	0.99885	0.99794	0.99669	0.99597	0
	Paris	0.99989	0.99967	0.99945	0.99930	0.99916	0
Germany	Berlin	n/a	0.99970	0.99949	0.99934	0.99938	1
	Munich	0.99999	0.99972	0.99948	0.99943	0.99916	0
	Rhein-Ruhr	1.000100	0.99990	0.99980	0.99972	0.99964	0
	Stuttgart	0.99993	0.99956	0.99941	0.99900	0.99920	1
Greece	Athens	0.99917	0.99799	0.99705	0.99618	0.99419	0
Italy	Milan	1.00010	0.99993	0.99985	0.99959	0.99951	0
	Rome	0.99939	0.99873	0.99798	0.99728	0.99636	0
	Turin	0.99918	0.99842	0.99764	0.99706	0.99644	0
	Naples	0.99883	0.99731	0.99560	0.99499	0.99420	0
Netherlands	Randstad	0.99982	0.99953	0.99927	0.99903	0.99909	1
Portugal	Lisbon	0.90992	0.99826	0.99737	0.99745	0.99683	1
Spain	Barcelona	0.99953	0.99881	0.99801	0.99747	0.99596	0
	Madrid	0.99972	0.99904	0.99830	0.99691	0.99640	0
	Valencia	0.99909	0.99819	0.99673	0.99569	0.99418	0
Sweden	Stockholm	0.99989	0.99927	0.99893	0.99857	0.99857	0
United Kingdom	London	0.99992	0.99980	0.99974	0.99966	0.99965	0
	Manchester	0.99953	0.99907	0.99892	0.99859	0.99828	0
	Leeds	0.99947	0.99906	0.99873	0.99878	0.99912	3
	Birmingham	0.99942	0.99877	0.99844	0.99845	0.99773	1
Ireland	Dublin	0.99923	0.99809	0.99676	0.99672	0.99627	0
Czech Republic	Prague	0.99989	0.99945	0.99923	0.99907	0.99892	0
Hungary	Budapest	1.00000	0.99947	0.99891	0.99859	0.99820	0
Poland	Warsaw	0.99899	0.99768	0.99647	0.99536	0.99653	2
		$\Theta_{12} = 0$	$\Theta_{23} = 0$	$\Theta_{34} = 3$	$\Theta_{45} = 5$		Total Ω = 11
			$\Theta_2 = 0$	$\Theta_3 = 3$	$\Theta_4 = 8$		

n/a Not available

Conceptual dimension of sprawl	2.2) Clustering
Operational dimension of sprawl	2.2.5) Index of Relative Clustering (RCL)

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Higher**

Country	Metropolitan area	Size of tessellated grid 1x1 km²	2x2 km²	3x3 km²	4x4 km²	5x5 km²	Ω
Austria	Vienna	-0.0102100	-0.003144	0.0021787	0.0079974	0.0133280	1
Belgium	Brussels	-0.0043563	-0.000850	0.0014374	0.0035770	0.0052974	0
Denmark	Copenhagen	-0.0073550	-0.003706	-0.0011930	-0.000889	0.0022393	0
Finland	Helsinki	-0.0069951	-0.005031	-0.002339	-0.000124	0.0026913	0
France	Lille	-0.0049211	-0.001893	0.0017399	0.0025706	0.0043529	0
	Lyon	-0.0030184	0.000469	0.0061162	0.0130160	0.0205050	0
	Paris	-0.0067214	-0.004986	-0.0038110	-0.002556	-0.0015760	0
Germany	Berlin	n/a	-0.006306	-0.001285	0.0002729	0.00099267	
	Munich	-0.0147360	-0.0116580	-0.008628	-0.0075780	-0.0044033	0
	Rhein-Ruhr	-0.0059881	-0.005228	-0.004014	-0.0031520	-0.0022098	
	Stuttgart	-0.0077393	-0.0035510	-0.000515	0.0030621	0.0039724	0
Greece	Athens	0.00094211	0.0061398	0.0083817	0.0100150	0.0083356	1
Italy	Milan	-0.0089662	-0.006579	-0.005208	-0.0037300	-0.0029875	0
	Rome	-0.0014612	0.0032020	0.0081258	0.0090618	0.01311500	0
	Turin	-0.0042495	-0.000992	0.0022741	0.0052147	0.0105100	0
	Naples	0.0080470	0.0209590	0.0318510	0.0356890	0.0479220	0
Netherlands	Randstad	-0.0000958	0.0003411	0.0006862	0.0019575	0.0027126	0
Portugal	Lisbon	0.00115910	0.0054282	0.0103470	0.0109940	0.0153560	0
Spain	Barcelona	-0.0027053	0.0002374	0.0033431	0.0063166	0.01371500	0
	Madrid	-0.0054377	-0.0031900	-0.00111600	0.0034685	0.0046060	0
	Valencia	-0.0024931	0.0002408	0.0054806	0.01018700	0.0173840	0
Sweden	Stockholm	-0.0120410	-0.0070280	-0.003643	-0.00107100	0.00111240	0
United Kingdom	London	-0.0055930	-0.0029810	-0.0013610	0.00027110	0.00118160	0
	Manchester	0.00019713	0.0016408	0.0023699	0.0037668	0.0070965	0
	Leeds	0.00028599	0.0023354	0.0030610	0.0029800	0.0016686	3
	Birmingham	0.00385560	0.0064994	0.0072782	0.0052066	0.0069437	1
Ireland	Dublin	-0.0043846	-0.000347	0.0013525	0.0019330	-0.0011524	1
Czech Republic	Prague	-0.0104570	-0.005005	-0.002834	0.0004248	0.0032558	0
Hungary	Budapest	-0.0097876	-0.0071140	-0.0038170	-0.0021930	0.0025489	0
Poland	Warsaw	-0.0009694	0.0031799	0.0101320	0.01793100	0.02126100	0
		$\Theta_{12} = 1$	$\Theta_{23} = 0$	$\Theta_{34} = 2$	$\Theta_{45} = 3$		Total
			$\Theta_{2} = 1$	$\Theta_{3} = 2$	$\Theta_{4} = 5$		Ω = 7

n/a Not available

Conceptual dimension of sprawl	2.3) Centralisation
Operational dimension of sprawl	2.3.1) Absolute Centralisation Index (ACE)

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Lower**

Country	Metropolitan area	Size of tessellated grid					Ω
		1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	
Austria	Vienna	0.85	0.83	0.82	0.82	0.82	0
Belgium	Brussels	0.84	0.83	0.83	0.83	0.83	0
Denmark	Copenhagen	0.77	0.71	0.71	0.69	0.70	1
Finland	Helsinki	0.83	0.80	0.78	0.75	0.76	1
France	Lille	0.82	0.80	0.80	0.79	0.79	0
	Lyon	0.76	0.73	0.73	0.72	0.73	1
	Paris	0.76	0.72	0.72	0.72	0.72	0
Germany	Berlin	0.80	0.79	0.79	0.78	0.78	0
	Munich	0.79	0.76	0.73	0.73	0.74	1
	Rhein-Ruhr	0.77	0.73	0.73	0.73	0.73	0
	Stuttgart	0.86	0.84	0.83	0.83	0.83	0
Greece	Athens	0.79	0.79	0.78	0.78	0.77	0
Italy	Milan	0.77	0.75	0.75	0.74	0.75	1
	Rome	0.83	0.81	0.80	0.79	0.79	0
	Turin	0.77	0.72	0.71	0.71	0.71	0
	Naples	0.83	0.81	0.81	0.80	0.79	0
Netherlands	Randstad	0.80	0.73	0.69	0.68	0.67	0
Portugal	Lisbon	0.74	0.72	0.73	0.74	0.74	5
Spain	Barcelona	0.81	0.76	0.73	0.73	0.72	0
	Madrid	0.78	0.71	0.69	0.68	0.67	0
	Valencia	0.78	0.71	0.68	0.66	0.66	0
Sweden	Stockholm	0.76	0.73	0.73	0.72	0.72	0
United Kingdom	London	0.81	0.79	0.78	0.78	0.78	0
	Manchester	0.75	0.72	0.72	0.72	0.71	0
	Leeds	0.75	0.75	0.75	0.75	0.75	0
	Birmingham	0.87	0.85	0.85	0.84	0.84	0
Ireland	Dublin	0.72	0.70	0.69	0.69	0.69	0
Czech Republic	Prague	0.72	0.70	0.70	0.70	0.70	0
Hungary	Budapest	0.74	0.69	0.69	0.67	0.68	1
Poland	Warsaw	0.65	0.62	0.62	0.62	0.61	0
		$\Theta_{12} = 0$	$\Theta_{23} = 1$	$\Theta_{34} = 1$	$\Theta_{45} = 6$		Total Ω = 11
			$\Theta_2 = 1$	$\Theta_3 = 2$	$\Theta_4 = 7$		

Conceptual dimension of sprawl	2.3) Centralisation
Operational dimension of sprawl	2.3.2) Relative Centralisation Index (RCE)

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **No pattern found**

Country	Metropolitan area	Size of tessellated grid					Ω
		1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	
Austria	Vienna	-0.08	-0.06	0.00	-0.15	-0.02	n/a
Belgium	Brussels	0.11	-0.35	-0.19	-0.04	-0.08	n/a
Denmark	Copenhagen	0.2	-0.29	0.17	-0.43	-0.27	n/a
Finland	Helsinki	0.17	0.20	0.21	-0.78	-0.45	n/a
France	Lille	-0.53	-0.10	-0.01	-0.14	-0.26	n/a
	Lyon	-0.14	-0.19	-0.06	-0.02	-0.02	n/a
	Paris	0.2	0.17	0.16	0.21	0.22	n/a
Germany	Berlin	0.14	0.15	0.18	0.06	0.00	n/a
	Munich	-0.58	0.05	-0.13	-0.29	-0.11	n/a
	Rhein-Ruhr	0.19	0.22	-0.11	-0.27	0.16	n/a
	Stuttgart	0.12	0.15	0.15	0.13	0.16	n/a
Greece	Athens	-0.18	-0.01	-0.18	-0.18	-0.09	n/a
Italy	Milan	0.16	0.19	-0.15	-0.21	-0.11	n/a
	Rome	0.12	0.16	0.05	0.04	0.07	n/a
	Turin	-0.41	0.02	-0.25	-0.25	-0.18	n/a
	Naples	0.08	-0.09	0.11	-0.24	-0.29	n/a
Netherlands	Randstad	0.22	0.28	0.31	0.32	0.04	n/a
Portugal	Lisbon	-0.71	-0.69	-0.34	-0.21	-0.14	n/a
Spain	Barcelona	-0.84	-0.17	0.08	-0.03	-0.24	n/a
	Madrid	-0.43	-0.03	-0.12	-0.24	-0.16	n/a
	Valencia	0.14	0.19	0.22	0.12	0.23	n/a
Sweden	Stockholm	0.18	0.22	0.23	0.11	0.05	n/a
United Kingdom	London	0.17	0.21	0.18	0.23	0.22	n/a
	Manchester	-0.12	0.01	-0.18	-0.15	-0.13	n/a
	Leeds	0.19	-0.19	0.06	-0.09	0.01	n/a
	Birmingham	0.16	0.17	0.17	0.17	0.15	n/a
Ireland	Dublin	-0.76	-0.73	-0.45	-0.24	-0.14	n/a
Czech Republic	Prague	-0.13	-0.18	-0.47	-0.24	-0.22	n/a
Hungary	Budapest	-0.71	-0.07	0.22	-0.28	-0.03	n/a
Poland	Warsaw	0.01	0.06	0.05	-0.17	-0.13	n/a
			Θ_{12} = n/a	Θ_{23} = n/a	Θ_{34} = n/a	Θ_{45} = n/a	Total Ω = n/a
			Θ_{2} = n/a	Θ_{3} = n/a	Θ_{4} = n/a		

n/a Not available

Conceptual dimension of sprawl		**3.1) Evenness**					
Operational dimension of sprawl		**3.1.1) Index of Dissimilarity (IOD′)**					
Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Lower**							

Country	Metropolitan area	Size of tessellated grid					Ω
		1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	
Austria	Vienna	0.87	0.77	0.68	0.62	0.59	0
Belgium	Brussels	0.85	0.71	0.61	0.52	0.45	0
Denmark	Copenhagen	0.81	0.66	0.61	0.55	0.50	0
Finland	Helsinki	0.77	0.63	0.56	0.48	0.43	0
France	Lille	0.8 1	0.66	0.57	0.50	0.46	0
	Lyon	0.74	0.58	0.51	0.47	0.42	0
	Paris	0.76	0.59	0.49	0.41	0.37	0
Germany	Berlin	0.82	0.69	0.61	0.56	0.50	0
	Munich	0.84	0.72	0.64	0.56	0.52	0
	Rhein-Ruhr	0.75	0.58	0.48	0.41	0.37	0
	Stuttgart	0.84	0.72	0.59	0.55	0.46	0
Greece	Athens	0.83	0.71	0.60	0.58	0.53	0
Italy	Milan	0.81	0.63	0.53	0.46	0.42	0
	Rome	0.85	0.73	0.62	0.58	0.53	0
	Turin	0.86	0.72	0.62	0.55	0.51	0
	Naples	0.90	0.79	0.73	0.65	0.57	0
Netherlands	Randstad	0.78	0.63	0.53	0.46	0.40	0
Portugal	Lisbon	0.80	0.65	0.58	0.49	0.44	0
Spain	Barcelona	0.86	0.73	0.66	0.58	0.55	0
	Madrid	0.84	0.72	0.64	0.60	0.56	0
	Valencia	0.87	0.74	0.69	0.62	0.61	0
Sweden	Stockholm	0.77	0.66	0.57	0.52	0.45	0
United Kingdom	London	0.76	0.59	0.48	0.41	0.35	0
	Manchester	0.68	0.49	0.36	0.30	0.28	0
	Leeds	0.70	0.50	0.39	0.32	0.25	0
	Birmingham	0.71	0.52	0.40	0.31	0.29	0
Ireland	Dublin	0.78	0.64	0.58	0.46	0.45	0
Czech Republic	Prague	0.80	0.67	0.59	0.52	0.46	0
Hungary	Budapest	0.82	0.69	0.60	0.54	0.48	0
Poland	Warsaw	0.70	0.55	0.47	0.41	0.32	0
		$\Theta_{12} = 0$	$\Theta_{23} = 0$	$\Theta_{34} = 0$	$\Theta_{45} = 0$		Total Ω = 0
			$\Theta_{2} = 0$	$\Theta_{3} = 0$	$\Theta_{4} = 0$		

Conceptual dimension of sprawl	3.1) Evenness
Operational dimension of sprawl	3.1.2) Gini Coefficient (GINI′)

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Lower**

Country	Metropolitan area	Size of tessellated grid					Ω
		1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	
Austria	Vienna	0.97	0.91	0.84	0.79	0.75	0
Belgium	Brussels	0.95	0.86	0.78	0.69	0.62	0
Denmark	Copenhagen	0.95	0.86	0.80	0.74	0.68	0
Finland	Helsinki	0.92	0.82	0.75	0.68	0.61	0
France	Lille	0.94	0.84	0.76	0.68	0.64	0
	Lyon	0.90	0.76	0.68	0.63	0.58	0
	Paris	0.92	0.78	0.68	0.58	0.52	0
Germany	Berlin	0.95	0.87	0.80	0.75	0.68	0
	Munich	0.96	0.89	0.81	0.74	0.70	0
	Rhein-Ruhr	0.91	0.78	0.66	0.58	0.51	0
	Stuttgart	0.95	0.87	0.76	0.72	0.61	0
Greece	Athens	0.96	0.89	0.80	0.76	0.72	0
Italy	Milan	0.94	0.81	0.72	0.63	0.59	0
	Rome	0.97	0.90	0.82	0.77	0.72	0
	Turin	0.97	0.88	0.79	0.72	0.65	0
	Naples	0.98	0.92	0.87	0.81	0.74	0
Netherlands	Randstad	0.93	0.82	0.72	0.63	0.56	0
Portugal	Lisbon	0.94	0.83	0.76	0.64	0.60	0
Spain	Barcelona	0.97	0.90	0.84	0.77	0.72	0
	Madrid	0.96	0.90	0.83	0.79	0.74	0
	Valencia	0.97	0.91	0.86	0.79	0.79	0
Sweden	Stockholm	0.93	0.85	0.76	0.71	0.63	0
United Kingdom	London	0.92	0.79	0.67	0.58	0.50	0
	Manchester	0.85	0.67	0.52	0.44	0.39	0
	Leeds	0.87	0.69	0.56	0.46	0.36	0
	Birmingham	0.87	0.69	0.56	0.45	0.42	0
Ireland	Dublin	0.93	0.83	0.77	0.64	0.62	0
Czech Republic	Prague	0.94	0.84	0.76	0.68	0.61	0
Hungary	Budapest	0.95	0.87	0.79	0.72	0.64	0
Poland	Warsaw	0.87	0.72	0.63	0.55	0.44	0
		$\Theta_{12} = 0$	$\Theta_{23} = 0$	$\Theta_{34} = 0$	$\Theta_{45} = 0$		Total Ω = 0
			$\Theta_2 = 0$	$\Theta_3 = 0$	$\Theta_4 = 0$		

Conceptual dimension of sprawl	3.1) Evenness
Operational dimension of sprawl	3.1.3) Atkinson Index with μ = 0.1 (AI.1)

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Lower**

Country	Metropolitan area	Size of tessellated grid					Ω
		1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	
Austria	Vienna	0.54	0.31	0.23	0.16	0.12	0
Belgium	Brussels	0.40	0.22	0.15	0.11	0.08	0
Denmark	Copenhagen	0.65	0.49	0.39	0.33	0.23	0
Finland	Helsinki	0.47	0.32	0.23	0.19	0.15	0
France	Lille	0.47	0.27	0.15	0.11	0.11	0
	Lyon	0.39	0.17	0.12	0.08	0.08	0
	Paris	0.42	0.20	0.12	0.07	0.06	0
Germany	Berlin	0.53	0.33	0.22	0.19	0.13	0
	Munich	0.54	0.35	0.21	0.16	0.12	0
	Rhein-Ruhr	0.39	0.18	0.11	0.07	0.05	0
	Stuttgart	0.45	0.23	0.14	0.12	0.08	0
Greece	Athens	0.63	0.44	0.33	0.28	0.16	0
Italy	Milan	0.47	0.23	0.17	0.09	0.07	0
	Rome	0.61	0.40	0.29	0.21	0.12	0
	Turin	0.56	0.29	0.17	0.12	0.09	0
	Naples	0.57	0.38	0.22	0.17	0.16	0
Netherlands	Randstad	0.56	0.32	0.22	0.14	0.10	0
Portugal	Lisbon	0.48	0.25	0.18	0.14	0.12	0
Spain	Barcelona	0.60	0.36	0.28	0.18	0.13	0
	Madrid	0.66	0.43	0.32	0.24	0.18	0
	Valencia	0.65	0.43	0.32	0.19	0.20	1
Sweden	Stockholm	0.55	0.39	0.31	0.25	0.21	0
United Kingdom	London	0.47	0.28	0.20	0.13	0.09	0
	Manchester	0.28	0.12	0.06	0.04	0.03	0
	Leeds	0.34	0.18	0.11	0.06	0.03	0
	Birmingham	0.25	0.12	0.07	0.05	0.04	0
Ireland	Dublin	0.58	0.38	0.26	0.18	0.15	0
Czech Republic	Prague	0.47	0.24	0.16	0.10	0.09	0
Hungary	Budapest	0.54	0.31	0.20	0.15	0.10	0
Poland	Warsaw	0.32	0.11	0.09	0.05	0.04	0
		Θ_{12} = 0	Θ_{23} = 0	Θ_{34} = 0	Θ_{45} = 1		Total Ω = 1
			Θ_2 = 0	Θ_3 = 0	Θ_4 = 1		

Conceptual dimension of sprawl	**3.1) Evenness**
Operational dimension of sprawl	**3.1.4) Atkinson Index with μ = 0.5 (AI.5)**

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Lower**

Country	**Metropolitan area**	**Size of tessellated grid**					**Ω**
		1x1 km²	**2x2 km²**	**3x3 km²**	**4x4 km²**	**5x5 km²**	
Austria	Vienna	0.94	0.84	0.74	0.66	0.58	0
Belgium	Brussels	0.91	0.75	0.62	0.51	0.42	0
Denmark	Copenhagen	0.90	0.76	0.66	0.57	0.49	0
Finland	Helsinki	0.86	0.70	0.59	0.50	0.42	0
France	Lille	0.89	0.72	0.60	0.50	0.45	0
	Lyon	0.82	0.59	0.48	0.41	0.35	0
	Paris	0.84	0.59	0.45	0.34	0.28	0
Germany	Berlin	0.91	0.77	0.66	0.59	0.49	0
	Munich	0.92	0.80	0.69	0.59	0.54	0
	Rhein-Ruhr	0.83	0.61	0.44	0.34	0.27	0
	Stuttgart	0.91	0.77	0.60	0.56	0.43	0
Greece	Athens	0.92	0.79	0.67	0.57	0.50	0
Italy	Milan	0.88	0.67	0.54	0.41	0.36	0
	Rome	0.93	0.82	0.69	0.61	0.52	0
	Turin	0.93	0.77	0.64	0.53	0.45	0
	Naples	0.95	0.85	0.76	0.68	0.61	0
Netherlands	Randstad	0.87	0.67	0.53	0.40	0.31	0
Portugal	Lisbon	0.89	0.69	0.58	0.44	0.38	0
Spain	Barcelona	0.93	0.81	0.71	0.59	0.52	0
	Madrid	0.93	0.80	0.70	0.63	0.56	0
	Valencia	0.95	0.83	0.75	0.64	0.61	0
Sweden	Stockholm	0.87	0.73	0.60	0.52	0.44	0
United Kingdom	London	0.85	0.63	0.47	0.36	0.27	0
	Manchester	0.73	0.47	0.28	0.22	0.15	0
	Leeds	0.76	0.49	0.34	0.23	0.15	0
	Birmingham	0.75	0.48	0.31	0.20	0.16	0
Ireland	Dublin	0.87	0.69	0.58	0.44	0.39	0
Czech Republic	Prague	0.88	0.73	0.62	0.52	0.44	0
Hungary	Budapest	0.90	0.75	0.62	0.52	0.43	0
Poland	Warsaw	0.76	0.51	0.41	0.30	0.22	0
		Θ_{12} = 0	Θ_{23} = 0	Θ_{34} = 0	Θ_{45} = 0		Total Ω = 0
			Θ_{2} = 0	Θ_{3} = 0	Θ_{4} = 0		

Conceptual dimension of sprawl	3.1) Evenness
Operational dimension of sprawl	**3.1.5) Atkinson Index with μ = 0.9 (AI.9)**

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Lower**

Country	Metropolitan area	Size of tessellated grid: 1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	Ω
Austria	Vienna	1.00	1.00	1.00	1.00	1.00	0
Belgium	Brussels	1.00	1.00	1.00	0.99	0.96	0
Denmark	Copenhagen	1.00	1.00	0.98	0.95	0.90	0
Finland	Helsinki	1.00	1.00	0.99	0.97	0.94	0
France	Lille	1.00	1.00	1.00	0.98	0.97	0
	Lyon	1.00	0.99	0.97	0.92	0.85	0
	Paris	1.00	0.98	0.93	0.85	0.77	0
Germany	Berlin	1.00	1.00	1.00	0.99	0.98	0
	Munich	1.00	1.00	1.00	1.00	0.99	0
	Rhein-Ruhr	1.00	0.99	0.95	0.87	0.77	0
	Stuttgart	1.00	1.00	1.00	0.99	0.98	0
Greece	Athens	1.00	1.00	0.99	0.95	0.92	0
Italy	Milan	1.00	1.00	0.98	0.94	0.91	0
	Rome	1.00	1.00	1.00	0.99	0.97	0
	Turin	1.00	1.00	1.00	0.99	0.96	0
	Naples	1.00	1.00	1.00	1.00	1.00	0
Netherlands	Randstad	1.00	0.99	0.93	0.82	0.71	0
Portugal	Lisbon	1.00	1.00	0.99	0.94	0.90	0
Spain	Barcelona	1.00	1.00	1.00	0.99	0.97	0
	Madrid	1.00	1.00	1.00	0.99	0.98	0
	Valencia	1.00	1.00	1.00	1.00	0.99	0
Sweden	Stockholm	1.00	1.00	0.98	0.95	0.89	0
United Kingdom	London	1.00	0.99	0.91	0.79	0.64	0
	Manchester	1.00	0.95	0.75	0.73	0.43	0
	Leeds	1.00	0.95	0.83	0.65	0.51	0
	Birmingham	1.00	0.96	0.80	0.53	0.30	0
Ireland	Dublin	1.00	0.99	0.95	0.86	0.85	0
Czech Republic	Prague	1.00	1.00	1.00	0.99	0.98	0
Hungary	Budapest	1.00	1.00	0.99	0.98	0.96	0
Poland	Warsaw	1.00	0.97	0.94	0.80	0.72	0
		Θ_{12} = 0	Θ_{23} = 0	Θ_{34} = 0	Θ_{45} = 0		Total Ω = 0
			Θ_2 = 0	Θ_3 = 0	Θ_4 = 0		

Conceptual dimension of sprawl	3.1) Evenness
Operational dimension of sprawl	3.1.6) Information Entropy Index (IEI′)

Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Lower**

Country	Metropolitan area	Size of tessellated grid					Ω
		1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	
Austria	Vienna	0.01	0.01	0.01	0.00	0.00	0
Belgium	Brussels	0.01	0.01	0.00	0.00	0.00	0
Denmark	Copenhagen	0.04	0.03	0.03	0.02	0.02	0
Finland	Helsinki	0.02	0.01	0.01	0.01	0.01	0
France	Lille	0.01	0.01	0.01	0.00	0.00	0
	Lyon	0.02	0.01	0.01	0.01	0.01	0
	Paris	0.02	0.01	0.01	0.01	0.00	0
Germany	Berlin	0.01	0.01	0.01	0.01	0.01	0
	Munich	0.01	0.01	0.01	0.01	0.00	0
	Rhein-Ruhr	0.01	0.01	0.01	0.00	0.00	0
	Stuttgart	0.01	0.01	0.00	0.00	0.00	0
Greece	Athens	0.03	0.02	0.02	0.02	0.02	0
Italy	Milan	0.01	0.01	0.01	0.00	0.00	0
	Rome	0.02	0.02	0.01	0.01	0.01	0
	Turin	0.02	0.01	0.01	0.01	0.01	0
	Naples	0.01	0.01	0.01	0.01	0.01	0
Netherlands	Randstad	0.03	0.02	0.02	0.01	0.01	0
Portugal	Lisbon	0.02	0.01	0.01	0.01	0.01	0
Spain	Barcelona	0.02	0.02	0.01	0.01	0.01	0
	Madrid	0.03	0.03	0.02	0.02	0.02	0
	Valencia	0.03	0.02	0.02	0.01	0.01	0
Sweden	Stockholm	0.02	0.02	0.02	0.01	0.01	0
United Kingdom	London	0.02	0.01	0.01	0.01	0.01	0
	Manchester	0.01	0.01	0.00	0.00	0.00	0
	Leeds	0.01	0.01	0.01	0.00	0.00	0
	Birmingham	0.01	0.01	0.00	0.00	0.00	0
Ireland	Dublin	0.03	0.02	0.02	0.01	0.01	0
Czech Republic	Prague	0.02	0.01	0.01	0.01	0.00	0
Hungary	Budapest	0.02	0.02	0.01	0.01	0.01	0
Poland	Warsaw	0.02	0.01	0.01	0.01	0.01	0
		Θ_{12} = 0	Θ_{23} = 0	Θ_{34} = 0	Θ_{45} = 0		Total Ω = 0
			Θ_2 = 0	Θ_3 = 0	Θ_4 = 0		

Conceptual dimension of sprawl			**3.1) Evenness**				
Operational dimension of sprawl			**3.1.7) Relative Entropy Index (REI)**				
Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Lower**							

Country	**Metropolitan area**	**Size of tessellated grid** 1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	**Ω**
Austria	Vienna	0.16	0.12	0.10	0.08	0.09	1
Belgium	Brussels	0.09	0.08	0.08	0.08	0.08	0
Denmark	Copenhagen	0.22	0.20	0.17	0.16	0.15	0
Finland	Helsinki	0.26	0.24	0.23	0.22	0.20	0
France	Lille	0.15	0.11	0.11	0.09	0.09	0
	Lyon	0.18	0.16	0.15	0.13	0.13	0
	Paris	0.13	0.10	0.09	0.07	0.07	0
Germany	Berlin	0.19	0.15	0.13	0.11	0.10	0
	Munich	0.20	0.16	0.13	0.12	0.11	0
	Rhein-Ruhr	0.12	0.10	0.08	0.08	0.07	0
	Stuttgart	0.17	0.13	0.11	0.10	0.09	0
Greece	Athens	0.24	0.22	0.20	0.20	0.18	0
Italy	Milan	0.16	0.14	0.12	0.12	0.11	0
	Rome	0.22	0.21	0.19	0.18	0.17	0
	Turin	0.23	0.20	0.18	0.16	0.16	0
	Naples	0.18	0.18	0.17	0.17	0.16	0
Netherlands	Randstad	0.21	0.19	0.17	0.17	0.16	0
Portugal	Lisbon	0.19	0.18	0.17	0.17	0.16	0
Spain	Barcelona	0.21	0.19	0.18	0.17	0.16	0
	Madrid	0.25	0.23	0.21	0.19	0.19	0
	Valencia	0.29	0.27	0.25	0.25	0.24	0
Sweden	Stockholm	0.26	0.25	0.24	0.23	0.21	0
United Kingdom	London	0.17	0.15	0.14	0.13	0.12	0
	Manchester	0.11	0.10	0.10	0.10	0.09	0
	Leeds	0.13	0.11	0.10	0.10	0.07	0
	Birmingham	0.12	0.12	0.12	0.11	0.09	0
Ireland	Dublin	0.27	0.26	0.24	0.22	0.20	0
Czech Republic	Prague	0.17	0.12	0.10	0.09	0.09	0
Hungary	Budapest	0.21	0.19	0.16	0.15	0.13	0
Poland	Warsaw	0.14	0.12	0.12	0.10	0.09	0
		$\Theta_{12} = 0$	$\Theta_{23} = 0$	$\Theta_{34} = 0$	$\Theta_{45} = 1$		Total Ω = 1
			$\Theta_2 = 0$	$\Theta_3 = 0$	$\Theta_4 = 1$		

Conceptual dimension of sprawl	3.2) Concentration
Operational dimension of sprawl	3.2.1) Delta (DEL)
Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Lower**	

Country	Metropolitan area	Size of tessellated grid					Ω
		1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	
Austria	Vienna	0.70	0.56	0.47	0.43	0.40	0
Belgium	Brussels	0.39	0.29	0.25	0.23	0.20	0
Denmark	Copenhagen	0.80	0.69	0.63	0.57	0.55	0
Finland	Helsinki	0.87	0.80	0.73	0.70	0.66	0
France	Lille	0.66	0.51	0.45	0.42	0.41	0
	Lyon	0.68	0.58	0.52	0.50	0.49	0
	Paris	0.67	0.56	0.52	0.49	0.47	0
Germany	Berlin	0.80	0.66	0.58	0.54	0.51	0
	Munich	0.80	0.67	0.58	0.52	0.47	0
	Rhein-Ruhr	0.61	0.50	0.44	0.40	0.38	0
	Stuttgart	0.73	0.58	0.48	0.43	0.40	0
Greece	Athens	0.78	0.71	0.67	0.64	0.62	0
Italy	Milan	0.68	0.56	0.49	0.46	0.43	0
	Rome	0.77	0.67	0.62	0.58	0.54	0
	Turin	0.82	0.70	0.63	0.57	0.53	0
	Naples	0.48	0.39	0.34	0.30	0.28	0
Netherlands	Randstad	0.71	0.60	0.51	0.48	0.42	0
Portugal	Lisbon	0.66	0.57	0.54	0.50	0.49	0
Spain	Barcelona	0.79	0.69	0.63	0.59	0.56	0
	Madrid	0.83	0.74	0.68	0.62	0.57	0
	Valencia	0.90	0.84	0.77	0.73	0.68	0
Sweden	Stockholm	0.88	0.83	0.77	0.74	0.71	0
United Kingdom	London	0.69	0.62	0.56	0.53	0.51	0
	Manchester	0.40	0.32	0.28	0.26	0.24	0
	Leeds	0.57	0.46	0.41	0.39	0.35	0
	Birmingham	0.28	0.23	0.22	0.20	0.20	0
Ireland	Dublin	0.88	0.83	0.78	0.74	0.72	0
Czech Republic	Prague	0.73	0.54	0.45	0.40	0.37	0
Hungary	Budapest	0.77	0.67	0.57	0.52	0.46	0
Poland	Warsaw	0.53	0.45	0.41	0.38	0.35	0
		$\Theta_{12} = 0$	$\Theta_{23} = 0$	$\Theta_{34} = 0$	$\Theta_{45} = 0$		Total Ω = 0
			$\Theta_2 = 0$	$\Theta_3 = 0$	$\Theta_4 = 0$		

Conceptual dimension of sprawl		**3.3) Exposure**					
Operational dimension of sprawl		**3.3.1) Interaction Index (INT)**					
Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Higher**							

Country	**Metropolitan area**	**Size of tessellated grid** 1x1 km^2	2x2 km^2	3x3 km^2	4x4 km^2	5x5 km^2	**Ω**
Austria	Vienna	0.04	0.06	0.08	0.09	0.10	0
Belgium	Brussels	0.05	0.08	0.10	0.11	0.11	0
Denmark	Copenhagen	0.10	0.16	0.19	0.22	0.24	0
Finland	Helsinki	0.09	0.13	0.15	0.17	0.18	0
France	Lille	0.06	0.10	0.12	0.14	0.14	0
	Lyon	0.11	0.17	0.19	0.20	0.21	0
	Paris	0.09	0.15	0.18	0.20	0.21	0
Germany	Berlin	0.07	0.10	0.13	0.14	0.15	0
	Munich	0.05	0.09	0.10	0.13	0.13	0
	Rhein-Ruhr	0.09	0.14	0.17	0.19	0.20	0
	Stuttgart	0.05	0.09	0.11	0.12	0.13	0
Greece	Athens	0.07	0.11	0.14	0.16	0.17	0
Italy	Milan	0.07	0.12	0.15	0.16	0.17	0
	Rome	0.05	0.09	0.11	0.13	0.14	0
	Turin	0.05	0.10	0.13	0.15	0.16	0
	Naples	0.03	0.06	0.07	0.09	0.09	0
Netherlands	Randstad	0.11	0.17	0.21	0.24	0.26	0
Portugal	Lisbon	0.08	0.13	0.15	0.18	0.19	0
Spain	Barcelona	0.06	0.09	0.12	0.14	0.15	0
	Madrid	0.07	0.12	0.15	0.17	0.19	0
	Valencia	0.06	0.10	0.12	0.15	0.15	0
Sweden	Stockholm	0.09	0.13	0.16	0.18	0.20	0
United Kingdom	London	0.09	0.14	0.17	0.18	0.20	0
	Manchester	0.11	0.15	0.17	0.18	0.19	0
	Leeds	0.11	0.16	0.18	0.20	0.21	0
	Birmingham	0.09	0.13	0.14	0.15	0.15	0
Ireland	Dublin	0.09	0.14	0.16	0.20	0.21	0
Czech Republic	Prague	0.08	0.12	0.15	0.17	0.18	0
Hungary	Budapest	0.08	0.12	0.15	0.18	0.20	0
Poland	Warsaw	0.13	0.19	0.22	0.24	0.25	0
		Θ_{12} = 0	Θ_{23} = 0	Θ_{34} = 0	Θ_{45} = 0		Total Ω = 0
			Θ_2 = 0	Θ_3 = 0	Θ_4 = 0		

Conceptual dimension of sprawl		**3.3) Exposure**					
Operational dimension of sprawl		**3.3.2) Eta Squared Index (ETA′)**					
Changing-degree pattern of the entire dataset when applying a larger grid size to the analysis: **Higher**							

Country	**Metropolitan area**	**Size of tessellated grid**					**Ω**
		1x1 km^2	**2x2 km^2**	**3x3 km^2**	**4x4 km^2**	**5x5 km^2**	
Austria	Vienna	0.30	0.48	0.61	0.67	0.75	0
Belgium	Brussels	0.36	0.59	0.69	0.70	0.83	0
Denmark	Copenhagen	0.27	0.43	0.51	0.58	0.64	0
Finland	Helsinki	0.37	0.55	0.63	0.70	0.76	0
France	Lille	0.35	0.56	0.66	0.74	0.77	0
	Lyon	0.39	0.62	0.70	0.74	0.78	0
	Paris	0.38	0.59	0.70	0.78	0.83	0
Germany	Berlin	0.31	0.49	0.59	0.65	0.72	0
	Munich	0.30	0.47	0.60	0.69	0.73	0
	Rhein-Ruhr	0.41	0.61	0.73	0.74	0.85	0
	Stuttgart	0.34	0.55	0.71	0.74	0.84	0
Greece	Athens	0.25	0.41	0.53	0.58	0.63	0
Italy	Milan	0.34	0.58	0.69	0.77	0.81	0
	Rome	0.26	0.43	0.54	0.61	0.67	0
	Turin	0.25	0.48	0.62	0.70	0.76	0
	Naples	0.25	0.46	0.57	0.67	0.73	0
Netherlands	Randstad	0.31	0.51	0.62	0.70	0.77	0
Portugal	Lisbon	0.33	0.54	0.63	0.74	0.78	0
Spain	Barcelona	0.25	0.43	0.53	0.62	0.68	0
	Madrid	0.23	0.40	0.50	0.56	0.62	0
	Valencia	0.22	0.40	0.47	0.58	0.58	0
Sweden	Stockholm	0.33	0.47	0.59	0.65	0.71	0
United Kingdom	London	0.37	0.57	0.69	0.76	0.82	0
	Manchester	0.53	0.73	0.84	0.89	0.92	0
	Leeds	0.47	0.69	0.79	0.86	0.91	0
	Birmingham	0.53	0.74	0.84	0.89	0.90	0
Ireland	Dublin	0.31	0.48	0.55	0.69	0.72	0
Czech Republic	Prague	0.34	0.53	0.65	0.73	0.79	0
Hungary	Budapest	0.28	0.47	0.58	0.66	0.74	0
Poland	Warsaw	0.45	0.66	0.74	0.81	0.87	0
		$\Theta_{12} = 0$	$\Theta_{23} = 0$	$\Theta_{34} = 0$	$\Theta_{45} = 0$		Total $\Omega = 0$
			$\Theta_2 = 0$	$\Theta_3 = 0$	$\Theta_4 = 0$		

APPENDIX I: SCENARIOS OF LAND-USE DISTRIBUTIONS WITH THE ESITMATED DEGREE OF ETA′

In order to gain more understanding in the dimension of 'exposure', various situations of land-use distributions are simulated in the city 'Z'. It contains sixteen subareas, Z_1 to Z_{16}, and all of them have potential to be developed (Figure 7.2). There are 12 scenarios that each subarea contains single land use in each subarea, 10 scenarios with both single-use subareas and mixed-use subareas, and 16 scenarios containing only mixed-use subareas.

Scenario illustrated in **Figure 7.3(a)**

Type of subarea: **single-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	0.00	16.00
Z_2	16.00	0.00
Z_3	0.00	16.00
Z_4	16.00	0.00
Z_5	0.00	16.00
Z_6	16.00	0.00
Z_7	0.00	16.00
Z_8	16.00	0.00
Z_9	0.00	16.00
Z_{10}	16.00	0.00
Z_{11}	0.00	16.00
Z_{12}	16.00	0.00
Z_{13}	0.00	16.00
Z_{14}	16.00	0.00
Z_{15}	0.00	16.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.3(b)**

Type of subarea: **single-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	0.00	16.00
Z_4	0.00	16.00
Z_5	16.00	0.00
Z_6	16.00	0.00
Z_7	0.00	16.00
Z_8	0.00	16.00
Z_9	16.00	0.00
Z_{10}	16.00	0.00
Z_{11}	0.00	16.00
Z_{12}	0.00	16.00
Z_{13}	16.00	0.00
Z_{14}	16.00	0.00
Z_{15}	0.00	16.00
Z_{16}	0.00	16.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.3(c)**

Type of subarea: **single-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	16.00	0.00
Z_4	16.00	0.00
Z_5	16.00	0.00
Z_6	16.00	0.00
Z_7	16.00	0.00
Z_8	16.00	0.00
Z_9	0.00	16.00
Z_{10}	0.00	16.00
Z_{11}	0.00	16.00
Z_{12}	0.00	16.00
Z_{13}	0.00	16.00
Z_{14}	0.00	16.00
Z_{15}	0.00	16.00
Z_{16}	0.00	16.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.3(d)**

Type of subarea: **single-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	0.00	16.00
Z_4	0.00	16.00
Z_5	16.00	0.00
Z_6	16.00	0.00
Z_7	0.00	16.00
Z_8	0.00	16.00
Z_9	0.00	16.00
Z_{10}	0.00	16.00
Z_{11}	16.00	0.00
Z_{12}	16.00	0.00
Z_{13}	0.00	16.00
Z_{14}	0.00	16.00
Z_{15}	16.00	0.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.3(e)**

Type of subarea: **single-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	0.00	16.00
Z_4	0.00	16.00
Z_5	0.00	16.00
Z_6	0.00	16.00
Z_7	16.00	0.00
Z_8	16.00	0.00
Z_9	16.00	0.00
Z_{10}	16.00	0.00
Z_{11}	0.00	16.00
Z_{12}	0.00	16.00
Z_{13}	0.00	16.00
Z_{14}	0.00	16.00
Z_{15}	16.00	0.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.3(f)**

Type of subarea: **single-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	0.00	16.00
Z_2	16.00	0.00
Z_3	0.00	16.00
Z_4	16.00	0.00
Z_5	0.00	16.00
Z_6	16.00	0.00
Z_7	0.00	16.00
Z_8	16.00	0.00
Z_9	16.00	0.00
Z_{10}	0.00	16.00
Z_{11}	16.00	0.00
Z_{12}	0.00	16.00
Z_{13}	16.00	0.00
Z_{14}	0.00	16.00
Z_{15}	16.00	0.00
Z_{16}	0.00	16.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.3(g)**

Type of subarea: **single-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	0.00	16.00
Z_4	16.00	0.00
Z_5	0.00	16.00
Z_6	0.00	16.00
Z_7	0.00	16.00
Z_8	16.00	0.00
Z_9	16.00	0.00
Z_{10}	0.00	16.00
Z_{11}	0.00	16.00
Z_{12}	0.00	16.00
Z_{13}	16.00	0.00
Z_{14}	0.00	16.00
Z_{15}	16.00	0.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.3(h)**

Type of subarea: **single-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	0.00	16.00
Z_2	0.00	16.00
Z_3	16.00	0.00
Z_4	0.00	16.00
Z_5	16.00	0.00
Z_6	16.00	0.00
Z_7	16.00	0.00
Z_8	0.00	16.00
Z_9	0.00	16.00
Z_{10}	16.00	0.00
Z_{11}	16.00	0.00
Z_{12}	16.00	0.00
Z_{13}	0.00	16.00
Z_{14}	16.00	0.00
Z_{15}	0.00	16.00
Z_{16}	0.00	16.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.4(a)**

Type of subarea: **single-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	16.00	0.00
Z_4	16.00	0.00
Z_5	16.00	0.00
Z_6	16.00	0.00
Z_7	16.00	0.00
Z_8	16.00	0.00
Z_9	16.00	0.00
Z_{10}	16.00	0.00
Z_{11}	0.00	16.00
Z_{12}	0.00	16.00
Z_{13}	16.00	0.00
Z_{14}	16.00	0.00
Z_{15}	0.00	16.00
Z_{16}	0.00	16.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.4(b)**

Type of subarea: **single-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	16.00	0.00
Z_4	16.00	0.00
Z_5	16.00	0.00
Z_6	0.00	16.00
Z_7	16.00	0.00
Z_8	16.00	0.00
Z_9	16.00	0.00
Z_{10}	16.00	0.00
Z_{11}	16.00	0.00
Z_{12}	0.00	16.00
Z_{13}	16.00	0.00
Z_{14}	0.00	16.00
Z_{15}	0.00	16.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.4(c)**

Type of subarea: **single-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	16.00	0.00
Z_4	16.00	0.00
Z_5	0.00	16.00
Z_6	0.00	16.00
Z_7	0.00	16.00
Z_8	0.00	16.00
Z_9	0.00	16.00
Z_{10}	0.00	16.00
Z_{11}	0.00	16.00
Z_{12}	0.00	16.00
Z_{13}	0.00	16.00
Z_{14}	0.00	16.00
Z_{15}	0.00	16.00
Z_{16}	0.00	16.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.4(d)**

Type of subarea: **single-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	0.00	16.00
Z_3	0.00	16.00
Z_4	0.00	16.00
Z_5	0.00	16.00
Z_6	16.00	0.00
Z_7	0.00	16.00
Z_8	0.00	16.00
Z_9	0.00	16.00
Z_{10}	0.00	16.00
Z_{11}	16.00	0.00
Z_{12}	0.00	16.00
Z_{13}	0.00	16.00
Z_{14}	0.00	16.00
Z_{15}	0.00	16.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0		

Scenario illustrated in **Figure 7.5(a)**

Type of subarea: **single-use subarea and mixed-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	0.30	15.70
Z_4	0.50	15.50
Z_5	16.00	0.00
Z_6	16.00	0.00
Z_7	0.41	15.59
Z_8	0.86	15.14
Z_9	0.90	15.10
Z_{10}	0.20	15.80
Z_{11}	16.00	0.00
Z_{12}	16.00	0.00
Z_{13}	0.56	15.44
Z_{14}	0.77	15.23
Z_{15}	16.00	0.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0.067462		

Scenario illustrated in **Figure 7.5(b)**

Type of subarea: **single-use subarea and mixed-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	1.32	14.68
Z_4	2.44	13.56
Z_5	16.00	0.00
Z_6	16.00	0.00
Z_7	1.12	14.88
Z_8	3.80	12.20
Z_9	2.97	13.03
Z_{10}	1.34	14.66
Z_{11}	16.00	0.00
Z_{12}	16.00	0.00
Z_{13}	3.50	12.50
Z_{14}	2.60	13.40
Z_{15}	16.00	0.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0.25211		

Scenario illustrated in **Figure 7.5(c)**

Type of subarea: **single-use subarea and mixed-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	8.00	8.00
Z_4	8.00	8.00
Z_5	16.00	0.00
Z_6	16.00	0.00
Z_7	8.00	8.00
Z_8	8.00	8.00
Z_9	8.00	8.00
Z_{10}	8.00	8.00
Z_{11}	16.00	0.00
Z_{12}	16.00	0.00
Z_{13}	8.00	8.00
Z_{14}	8.00	8.00
Z_{15}	16.00	0.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0.66667		

Scenario illustrated in **Figure 7.5(d)**

Type of subarea: **single-use subarea and mixed-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	14.68	1.32
Z_4	13.56	2.44
Z_5	16.00	0.00
Z_6	16.00	0.00
Z_7	14.88	1.12
Z_8	12.20	3.80
Z_9	13.03	2.97
Z_{10}	14.66	1.34
Z_{11}	16.00	0.00
Z_{12}	16.00	0.00
Z_{13}	12.50	3.50
Z_{14}	13.40	2.60
Z_{15}	16.00	0.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0.89302		

Scenario illustrated in **Figure 7.5(e)**

Type of subarea: **single-use subarea and mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	16.00	0.00
Z_2	16.00	0.00
Z_3	15.70	0.30
Z_4	15.50	0.50
Z_5	16.00	0.00
Z_6	16.00	0.00
Z_7	15.59	0.41
Z_8	15.14	0.86
Z_9	15.10	0.90
Z_{10}	15.80	0.20
Z_{11}	16.00	0.00
Z_{12}	16.00	0.00
Z_{13}	15.44	0.56
Z_{14}	15.23	0.77
Z_{15}	16.00	0.00
Z_{16}	16.00	0.00
Estimated degree of ETA′ = 0.97542		

Scenario illustrated in **Figure 7.5(f)**

Type of subarea: **single-use subarea and mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	15.70	0.30
Z_2	15.50	0.50
Z_3	0.00	16.00
Z_4	0.00	16.00
Z_5	15.59	0.41
Z_6	15.14	0.86
Z_7	0.00	16.00
Z_8	0.00	16.00
Z_9	0.00	16.00
Z_{10}	0.00	16.00
Z_{11}	15.10	0.90
Z_{12}	15.80	0.20
Z_{13}	0.00	16.00
Z_{14}	0.00	16.00
Z_{15}	15.44	0.56
Z_{16}	15.23	0.77
Estimated degree of ETA′ = 0.067462		

Scenario illustrated in **Figure 7.5(g)**

Type of subarea: **single-use subarea and mixed-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	14.68	1.32
Z_2	13.56	2.44
Z_3	0.00	16.00
Z_4	0.00	16.00
Z_5	14.88	1.12
Z_6	12.20	3.80
Z_7	0.00	16.00
Z_8	0.00	16.00
Z_9	0.00	16.00
Z_{10}	0.00	16.00
Z_{11}	13.03	2.97
Z_{12}	14.66	1.34
Z_{13}	0.00	16.00
Z_{14}	0.00	16.00
Z_{15}	12.50	3.50
Z_{16}	13.40	2.60
Estimated degree of ETA′ = 0.25211		

Scenario illustrated in **Figure 7.5(h)**

Type of subarea: **single-use subarea and mixed-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	8.00	8.00
Z_2	8.00	8.00
Z_3	0.00	16.00
Z_4	0.00	16.00
Z_5	8.00	8.00
Z_6	8.00	8.00
Z_7	0.00	16.00
Z_8	0.00	16.00
Z_9	0.00	16.00
Z_{10}	0.00	16.00
Z_{11}	8.00	8.00
Z_{12}	8.00	8.00
Z_{13}	0.00	16.00
Z_{14}	0.00	16.00
Z_{15}	8.00	8.00
Z_{16}	8.00	8.00
Estimated degree of ETA′ = 0.66667		

Scenario illustrated in **Figure 7.5(i)**

Type of subarea: **single-use subarea and mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	1.32	14.68
Z_2	2.44	13.56
Z_3	0.00	16.00
Z_4	0.00	16.00
Z_5	1.12	14.88
Z_6	3.80	12.20
Z_7	0.00	16.00
Z_8	0.00	16.00
Z_9	0.00	16.00
Z_{10}	0.00	16.00
Z_{11}	2.97	13.03
Z_{12}	1.34	14.66
Z_{13}	0.00	16.00
Z_{14}	0.00	16.00
Z_{15}	3.50	12.50
Z_{16}	2.60	13.40
Estimated degree of ETA′ = 0.89302		

Scenario illustrated in **Figure 7.5(j)**

Type of subarea: **single-use subarea and mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	0.30	15.70
Z_2	0.50	15.50
Z_3	0.00	16.00
Z_4	0.00	16.00
Z_5	0.41	15.59
Z_6	0.86	15.14
Z_7	0.00	16.00
Z_8	0.00	16.00
Z_9	0.00	16.00
Z_{10}	0.00	16.00
Z_{11}	0.90	15.10
Z_{12}	0.20	15.80
Z_{13}	0.00	16.00
Z_{14}	0.00	16.00
Z_{15}	0.56	15.44
Z_{16}	0.77	15.23
Estimated degree of ETA′ = 0.97542		

Scenario illustrated in **Figure 7.6(a)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	15.70	0.30
Z_2	15.50	0.50
Z_3	0.30	15.70
Z_4	0.50	15.50
Z_5	15.59	0.41
Z_6	15.14	0.86
Z_7	0.41	15.59
Z_8	0.86	15.14
Z_9	0.90	15.10
Z_{10}	0.20	15.80
Z_{11}	15.10	0.90
Z_{12}	15.80	0.20
Z_{13}	0.56	15.44
Z_{14}	0.77	15.23
Z_{15}	15.44	0.56
Z_{16}	15.23	0.77
Estimated degree of ETA′ = 0.13476		

Scenario illustrated in **Figure 7.6(b)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	15.70	0.30
Z_2	15.50	0.50
Z_3	1.32	14.68
Z_4	2.44	13.56
Z_5	15.59	0.41
Z_6	15.14	0.86
Z_7	1.12	14.88
Z_8	3.80	12.20
Z_9	2.97	13.03
Z_{10}	1.34	14.66
Z_{11}	15.10	0.90
Z_{12}	15.80	0.20
Z_{13}	3.50	12.50
Z_{14}	2.60	13.40
Z_{15}	15.44	0.56
Z_{16}	15.23	0.77
Estimated degree of ETA′ = 0.31802		

Scenario illustrated in **Figure 7.6(c)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	15.70	0.30
Z_2	15.50	0.50
Z_3	8.00	8.00
Z_4	8.00	8.00
Z_5	15.59	0.41
Z_6	15.14	0.86
Z_7	8.00	8.00
Z_8	8.00	8.00
Z_9	8.00	8.00
Z_{10}	8.00	8.00
Z_{11}	15.10	0.90
Z_{12}	15.80	0.20
Z_{13}	8.00	8.00
Z_{14}	8.00	8.00
Z_{15}	15.44	0.56
Z_{16}	15.23	0.77
Estimated degree of ETA′ = 0.72377		

Scenario illustrated in **Figure 7.6(d)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	15.70	0.30
Z_2	15.50	0.50
Z_3	14.68	1.32
Z_4	13.56	2.44
Z_5	15.59	0.41
Z_6	15.14	0.86
Z_7	14.88	1.12
Z_8	12.20	3.80
Z_9	13.03	2.97
Z_{10}	14.66	1.34
Z_{11}	15.10	0.90
Z_{12}	15.80	0.20
Z_{13}	12.50	3.50
Z_{14}	13.40	2.60
Z_{15}	15.44	0.56
Z_{16}	15.23	0.77
Estimated degree of ETA′ = 0.93801		

Scenario illustrated in **Figure 7.6(e)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	15.70	0.30
Z_2	15.50	0.50
Z_3	15.72	0.28
Z_4	15.10	0.90
Z_5	15.59	0.41
Z_6	15.14	0.86
Z_7	15.20	0.80
Z_8	15.59	0.41
Z_9	15.70	0.30
Z_{10}	15.30	0.70
Z_{11}	15.10	0.90
Z_{12}	15.80	0.20
Z_{13}	15.77	0.23
Z_{14}	15.38	0.62
Z_{15}	15.44	0.56
Z_{16}	15.23	0.77
Estimated degree of ETA′ = 0.99301		

Scenario illustrated in **Figure 7.6(f)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	14.68	1.32
Z_2	13.56	2.44
Z_3	0.30	15.70
Z_4	0.50	15.50
Z_5	14.88	1.12
Z_6	12.20	3.80
Z_7	0.41	15.59
Z_8	0.86	15.14
Z_9	0.90	15.10
Z_{10}	0.20	15.80
Z_{11}	13.03	2.97
Z_{12}	14.66	1.34
Z_{13}	0.56	15.44
Z_{14}	0.77	15.23
Z_{15}	12.50	3.50
Z_{16}	13.40	2.60
Estimated degree of ETA′ = 0.31802		

Scenario illustrated in **Figure 7.6(g)**

Type of subarea: **mixed-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	14.68	1.32
Z_2	13.56	2.44
Z_3	1.32	14.68
Z_4	2.44	13.56
Z_5	14.88	1.12
Z_6	12.20	3.80
Z_7	1.12	14.88
Z_8	3.80	12.20
Z_9	2.97	13.03
Z_{10}	1.34	14.66
Z_{11}	13.03	2.97
Z_{12}	14.66	1.34
Z_{13}	3.50	12.50
Z_{14}	2.60	13.40
Z_{15}	12.50	3.50
Z_{16}	13.40	2.60
Estimated degree of ETA′ = 0.49301		

Scenario illustrated in **Figure 7.6(h)**

Type of subarea: **mixed-use subarea**

Subarea	**Residential land area (km^2)**	**Non-residential land area (km^2)**
Z_1	14.68	1.32
Z_2	13.56	2.44
Z_3	8.00	8.00
Z_4	8.00	8.00
Z_5	14.88	1.12
Z_6	12.20	3.80
Z_7	8.00	8.00
Z_8	8.00	8.00
Z_9	8.00	8.00
Z_{10}	8.00	8.00
Z_{11}	13.03	2.97
Z_{12}	14.66	1.34
Z_{13}	8.00	8.00
Z_{14}	8.00	8.00
Z_{15}	12.50	3.50
Z_{16}	13.40	2.60
Estimated degree of ETA′ = 0.8513		

Scenario illustrated in **Figure 7.6(i)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	14.68	1.32
Z_2	13.56	2.44
Z_3	14.68	1.32
Z_4	13.56	2.44
Z_5	14.88	1.12
Z_6	12.20	3.80
Z_7	14.88	1.12
Z_8	12.20	3.80
Z_9	13.03	2.97
Z_{10}	14.66	1.34
Z_{11}	13.03	2.97
Z_{12}	14.66	1.34
Z_{13}	12.50	3.50
Z_{14}	13.40	2.60
Z_{15}	12.50	3.50
Z_{16}	13.40	2.60
Estimated degree of ETA′ = 0.97128		

Scenario illustrated in **Figure 7.6(j)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	14.68	1.32
Z_2	13.56	2.44
Z_3	15.70	0.30
Z_4	15.50	0.50
Z_5	14.88	1.12
Z_6	12.20	3.80
Z_7	15.59	0.41
Z_8	15.14	0.86
Z_9	15.10	0.90
Z_{10}	15.80	0.20
Z_{11}	13.03	2.97
Z_{12}	14.66	1.34
Z_{13}	15.44	0.56
Z_{14}	15.23	0.77
Z_{15}	12.50	3.50
Z_{16}	13.40	2.60
Estimated degree of ETA′ = 0.93801		

Scenario illustrated in **Figure 7.6(k)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	8.00	8.00
Z_2	8.00	8.00
Z_3	0.30	15.70
Z_4	0.50	15.50
Z_5	8.00	8.00
Z_6	8.00	8.00
Z_7	0.41	15.59
Z_8	0.86	15.14
Z_9	0.90	15.10
Z_{10}	0.20	15.80
Z_{11}	8.00	8.00
Z_{12}	8.00	8.00
Z_{13}	0.56	15.44
Z_{14}	0.77	15.23
Z_{15}	8.00	8.00
Z_{16}	8.00	8.00
Estimated degree of ETA′ = 0.72377		

Scenario illustrated in **Figure 7.6(l)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area km^2)
Z_1	8.00	8.00
Z_2	8.00	8.00
Z_3	1.32	14.68
Z_4	2.44	13.56
Z_5	8.00	8.00
Z_6	8.00	8.00
Z_7	1.12	14.88
Z_8	3.80	12.20
Z_9	2.97	13.03
Z_{10}	1.34	14.66
Z_{11}	8.00	8.00
Z_{12}	8.00	8.00
Z_{13}	3.50	12.50
Z_{14}	2.60	13.40
Z_{15}	8.00	8.00
Z_{16}	8.00	8.00
Estimated degree of ETA′ = 0.8513		

Scenario illustrated in **Figure 7.6(m)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	8.00	8.00
Z_2	8.00	8.00
Z_3	8.00	8.00
Z_4	8.00	8.00
Z_5	8.00	8.00
Z_6	8.00	8.00
Z_7	8.00	8.00
Z_8	8.00	8.00
Z_9	8.00	8.00
Z_{10}	8.00	8.00
Z_{11}	8.00	8.00
Z_{12}	8.00	8.00
Z_{13}	8.00	8.00
Z_{14}	8.00	8.00
Z_{15}	8.00	8.00
Z_{16}	8.00	8.00
Estimated degree of ETA′ = 1.00		

Scenario illustrated in **Figure 7.6(n)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	8.00	8.00
Z_2	8.00	8.00
Z_3	14.68	1.32
Z_4	13.56	2.44
Z_5	8.00	8.00
Z_6	8.00	8.00
Z_7	14.88	1.12
Z_8	12.20	3.80
Z_9	13.03	2.97
Z_{10}	14.66	1.34
Z_{11}	8.00	8.00
Z_{12}	8.00	8.00
Z_{13}	12.50	3.50
Z_{14}	13.40	2.60
Z_{15}	8.00	8.00
Z_{16}	8.00	8.00
Estimated degree of ETA′ = 0.8513		

Scenario illustrated in **Figure 7.6(o)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	8.00	8.00
Z_2	8.00	8.00
Z_3	15.72	0.28
Z_4	15.10	0.90
Z_5	8.00	8.00
Z_6	8.00	8.00
Z_7	15.20	8.00
Z_8	15.59	0.41
Z_9	15.70	0.30
Z_{10}	15.30	0.70
Z_{11}	8.00	8.00
Z_{12}	8.00	8.00
Z_{13}	15.77	0.23
Z_{14}	15.38	0.62
Z_{15}	8.00	8.00
Z_{16}	8.00	8.00
Estimated degree of ETA′ = 0.72069		

Scenario illustrated in **Figure 7.6(p)**

Type of subarea: **mixed-use subarea**

Subarea	Residential land area (km^2)	Non-residential land area (km^2)
Z_1	3.00	13.00
Z_2	3.00	13.00
Z_3	3.00	13.00
Z_4	3.00	13.00
Z_5	3.00	13.00
Z_6	3.00	13.00
Z_7	3.00	13.00
Z_8	3.00	13.00
Z_9	3.00	13.00
Z_{10}	3.00	13.00
Z_{11}	3.00	13.00
Z_{12}	3.00	13.00
Z_{13}	3.00	13.00
Z_{14}	3.00	13.00
Z_{15}	3.00	13.00
Z_{16}	3.00	13.00
Estimated degree of ETA′ = 1.00		