Building Densities

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A Physical Volume Approach

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Dissertation submitted in fulfilment of requirements for the Degree of
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August 2004

Abstract

Major modern cities in Western Europe are becoming increasingly dominated by high rise buildings, or skyscrapers. As the competition for useable land space grows, the desire for tall structures also progresses. Their high-intensity use of this land affects the dynamics of the city. From infrastructure to population movement to aesthetics, the effect of the modern skyscraper can no longer be taken for granted. In general planning terms, it is important to be able to locate and quantify the effect that these zones have on the makeup of the city. Until recently, most urban studies have focused on abstract measures of population and functions (number of coexisting land uses) across the city. These studies take for granted the true physical properties of the structures in which they exist. The emergence of new high detail data has made it possible to study, with great detail, the characteristics of these high rise zones. Presented in this thesis is a methodology for determining urban volume, a value calculated using building heights, to measure density within city zones. This process can be used for studying the patterns and inherent spatial characteristics of the city – as is showcased in two case studies selected in the western Netherlands.

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DISCLAIMER

The results presented in this dissertation are based on my own research at the Vrije Universiteit Amsterdam. All assistance received from other individuals and organisations has been acknowledged and full reference is made to all published and unpublished sources used.

This thesis has not been submitted previously for a degree at any Institution.

Signed:

Date:

Acknowledgements

I would like to express my sincere thanks to those individuals who have made this thesis and my degree possible. Firstly, to Prof. Paul van Helden of the University of Pretoria for pushing my application to study in The Netherlands; and to Prof. Henk Scholten, Mathilde Molendijk and the SPINlab team at the Vrije Universiteit for making it possible (and ultimately worthwhile) through the DELTA program. I have had a life-enhancing experience living in Amsterdam and working with the SPINlab – one that I will never forget.

Secondly, I would like to thank Eric Koomen for his tireless efforts in supervising and sculpting this thesis. His innovative comments and sometimes-conflicting views have had a significant influence on this submitted product and his effort is greatly appreciated. Work related to this research was also presented by Eric in April at the AGILE2004 GIS conference in Crete, which was well received.

Lastly, I would like to thank those individuals who offered the crucial data used as the backbone of this research. Mrs. Jean Huizing of the Adviesdienst Geo-informatie en ICT (Geo-Loket) of the Rijkswaterstaat for supplying, without charge, the essential height data sets, without which this thesis would not be possible. Also to the spatial planning department of the Amsterdam Municipality (DRO) for supplying the full building-date data set.

On a personal note, I would like to sincerely thank the people with whom I spent most of my 10 months with – the IVM at the Vrije Universteit. Its personnel and enjoyable working environment made the hard grind of this thesis just a little bit more bearable. Most of all, thanks to A-603 for putting up with my antics for almost a year – we are all better people as because of it.

Chapter 1

Introduction

"The generic city is 'a post city being prepared on the site of the ex-city'. It is not bound together by the public domain, the agora, but by the residue. The street is dead; the skyscraper has become the definitive typology. It has swallowed up all the rest and can stand where it likes, aloof and untouchable..." Lieven De Cauter, 1998.

1.1. Cities and their morphology

The modern city has many faces. It is the functional centre of our society; the heartbeat of the economy, industry, commerce and culture; and is a melting pot of both old and new. Each city, and each region within a city, similarly has different functions, styles and ultimately spatial patterns. One aspect of the urban zone is its propensity to grow relentlessly. Through the ages, growing cities have been sustained by innovations in technology that make it possible for millions of people to work and live in an increasingly confined space. The space itself is finite, it cannot be extended indefinitely – some solutions to alleviate this fact include the reclamation of land, use of underground space and land use densification. The latter is the focus of this thesis.

The development of cities into the vertical dimension is not a recent phenomenon, nor is it confined to specific urban areas. Ancient cities all over the globe have made use of some multi-functional and multi-storey buildings to house more useable space in a limited ground area – including vast numbers of tall structures such as church spires, guard towers and colloseums. However, there have been certain limitations to this 3 dimensional progress – weak building foundations, inadequate architecture/building skills, sanitation capabilities, societal problems and physical barriers (Fitchen, 1986). These physical barriers have restricted the heights of buildings to around 4 or 5 storeys. The most influential technological solution to this problem came somewhat before the discovery of stronger and lighter building materials (reinforced concrete, steel) – the invention of the elevator. The elevator as we know it today had its first incarnation in 1852 (Pacione, 2001). Slowly these innovations transformed the modern city skyline, with an apparent disregard for the laws of physics.

The space-race for useable land use in urban areas has sparked policy that encourages urban renewal and the densification of derelict inner-urban areas. Cities in Europe and the USA differ greatly in their spatial characteristics – in Europe the traditional centre has remained pivotal in the functioning of the city, whereas in the transport-centred USA, the Central Business District (CBD) has become a poster for social decay (Pacione, 2001). Despite this fundamental difference, on both sides of the Atlantic, policy is being introduced and implemented to reuse and regenerate the status of the older town centres in order to minimise commuting distances in the ever expanding city (Bento *et al*, 2002).

The attempts of researchers to understand the spatial pattern of cities is well founded in modern literature; they have developed methods of quantifying gradients, densities and diversity in terms of population and functions in order to better understand the urban machine. These indicators are abstract in nature – they attempt to quantify uses and populations in order to model the physical city. The use of these methods leads to studies that focus predominantly on the two primary dimensions. The growth of the physical city skywards has prompted a renewed vision for including this aspect in studies undertaken to understand various urban phenomena (Batty, 2000). The inclusion of building heights in urban study is not entirely novel, however, this thesis offers an alternative methodology for describing and quantifying the intensity of land use in urban areas so as to better understand the influence that tall skyscrapers have on city morphology.

1.2. The study

1.2.1. *Problem setting*

It is undeniable that the modern city is characterised by more than two simple dimensions. As a result it is important to find methods of visualising and studying urban areas in terms of their 3 physical dimensions. The pursuit of this thesis is to create a generic method of creating data for studying physical urban structures and their density by exploiting current technological trends in terms of both software and data. With an increasing urban population in Western Europe and much of the world, focusing on these areas to accomplish this objective is justified, and with new high-resolution, high-accuracy height data available, it is also feasible.

1.2.2. *Problem statement*

The intention of this thesis is to develop a method for quantifying physical urban density by exploiting current GIS technology and newly available high detail data sets. It concentrates on The Netherlands, in what is essentially a 4 dimensional study of urban volume. The primary objective is to create a generic and repeatable methodology that can generate volume data for any urban area. The methodology is then used in two applications to test its capabilities. The first case study is a time-series investigation of the Amsterdam urban area from 1900 to 2000. The analysis attempts to explore the form of- and change in physical density by using a combination of highly detailed data sets within a commercial GISoftware environment. The results are studied to extract information regarding the patterns of urban settlement and provide a quantitative analysis of the change in density that has occurred in the area. Each time interval reveals where and when the physical density has been focused and changed. In order to accomplish these goals some research into urban patterns and traditional urban pattern study is included. Much of the focus in town and regional planning (and other disciplines) is placed on describing the 'urban' in order to facilitate better service provision. A literature review shows how this investigation complements current research agendas.

The second case study creates congruent data sets in the four major cities in the Randstad region of The Netherlands. Similar to the first case study, this application creates volume data for urban areas and calculates an 'urban volume' indicator that is used to compare densities in the different cities. Some standard statistical analysis techniques are also used. The results are again compared with some traditional ideas about urban structure.

To summarise these ambitions, the following title is offered: **Building Densities – A Physical Volume Approach.** This title alludes to the important aspects of the study as well as its inherent restrictions. The research aims to study the density of physical structures (buildings) in urban areas using their physical volume as a proxy for density. A secondary aim of the thesis is to test the applicability of GIS technology and high detail data sets to the academic field of urban study. In order to restrict the analysis to a homogenous category, the Netherlands has been selected to offer case studies.

To clarify the nature of the statements above, some definitions of the concepts are now offered. The focus on the structural urban density of a city refers to the density in terms of buildings and structures – i.e. physical density. The aim is to measure an aspect of the urban fabric that is analogous to human perception. The people of a city perceive the 'level of density' in terms of (among others) the size and 'closeness' of the buildings and structures around them. This study aims at this perception and attempts to quantify it. The availability of highly detailed height datasets in the Netherlands makes this study feasible. An integration of available datasets provides data that describes the location and height (density) of all structures in the chosen regions – and in the Amsterdam case, at any given year in the past century. The combination of these dimensions describes the four dimensions of the urban landscape.

The study is reliant on the ability of GIS to perform the required tasks. In all the procedures described later in the thesis, GIS is used as the core tool to store, create and analyse the data. In addition, some attention is paid to the use of some new tools offered by GIS in terms of 3D visualisation. As this study claims to be of 4 dimensions, the ability of GIS to provide a framework for describing this high-dimensional data is invaluable. This thesis shows the applicability of the technology to the field of urban geography.

1.2.3. *Research questions*

To specify these ideas and goals, the following formal research questions have been defined. The final chapter of the thesis evaluates the results of these questions.

- Can a new complementary methodology for describing urban space be created by quantifying building volume and density?
- Can the morphology of a city be meaningfully described by such an urban volume layer in a reproducible manner? – this is investigated in two case studies:
    - *Amsterdam time series study*:
        - Can this study of densities show the rising/decreasing importance of polynuclearity in the city?
        - Can areas of high intensity land use be discovered?
    - *Randstad region case study*:
        - Can the spatial characteristics of density be normalised and compared between the four major cities of the region?

1.2.4. *Thesis layout*

In order to achieve the goals set out for this research, the following methodology will be employed. The dissertation is divided into three main subsections of theory, practice and evaluation; further subdivisions can be described as follows:

- Theoretical subsection:
  - Urban density study, current methods, practices and foci.
  - Technological abilities of GIS – with relevance to physical urban land use study.
  - Data issues.
  - Urban density methodology.
  - What are the applicable areas for using these technologies and has this been attempted already (and in what way)?
- Practical subsection:
  - Case study: Densities over Time – Changes in Amsterdam.
  - Case study: Densities over Space – Comparison in The Randstad.
- Evaluation subsection:
  - Evaluation of theory and practice.
  - Conclusions and recommendations.

An initial inquisition into the related fields of study provides a theoretical grounding for the research – including some ideas as to where the current opportunities lie and where possible improvements can be made. The important sub sections of this investigation are physical urban study, density studies and GIS/data and their interrelationships. With this core focal area defined, an in-depth discussion into the proposed solution(s) is provided along with some alternative possibilities and a current research review. This includes an investigation into current technologies that can be applied to assist in the tasks. With these investigations complete, a practical test application of the ideas expressed is conducted in two case studies within The Netherlands. The time-series case study is carried out for the city of Amsterdam and the comparison case study is applied to the four major cities of the Randstad region. With these studies completed, an evaluation of the test cases is presented. Issues pertaining to completeness, effectiveness and applicability are dealt with – as well as conclusions in comparison with the outlaid hypotheses and expected outcomes from preceding chapters. The study is then rounded off by offering overall conclusions and recommendations – in terms of study, data and technology. Figure 1.1 offers a visual interpretation of this outline.

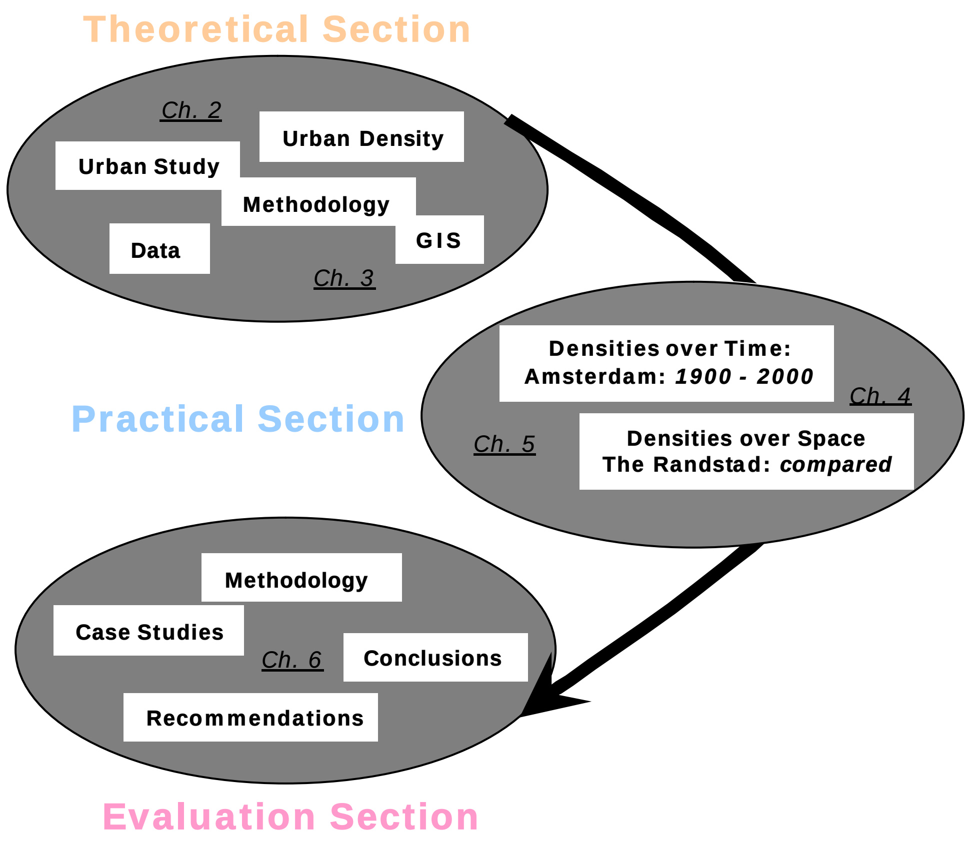


Figure 1.1. The flow of the dissertation: a theoretical background, practical applications and an evaluation.

1.2.5. *Overview of chapters*

The table below (Table 1.1) explains which topics are covered in each chapter of the thesis, in relation to the layout described above.

Chapter	**Contents**
1	An introduction to the study. Background into the changing urban settlement and the need for an improvement in the related spatial sciences. Highlights the aims and objectives of the study – including the research questions. Provides the layout of the thesis and the methodology to be followed.

2	Introduces the concepts of physical urban study, GIS and their inter-relationship. Urban density is discussed in terms of its relation to general urban study; urban study in The Netherlands and current approaches are included. Some ideas on current GIS and data trends and their usefulness to the proposed application are provided.
3	Discussion of the urban density measure (indicator); the urban volume methodology; data requirements and treatment; and issues relating to the implementation into a commercial GISoftware package(s). An introduction into the proposed case studies applications.
4	Amsterdam case study: investigates the changes in the city's density between 1900 and 2000. Includes a background in the city's development, the hypothesis, implementation discussion, results and a review.
5	Randstad case study: comparison of the densities in the four major cities of the Randstad region. As in Chapter 4, a general background, hypothesis, implementation discussion, results and a review are offered.
6	The final conclusion and evaluation chapter summarises the thesis. It offers some overall impressions and discusses the meeting of original goals and aims – i.e. comparison to the original research questions. It also offers some ideas on possible improvements and future research avenues.

Table 1.1. Short explanation of the chapters of this thesis.

Chapter 2

Urban density studies and GIS, *in context*

> *"Much of regional science remains avowedly deductive in its quest for generalisations about spatial distributions, and has scarcely acknowledged the tide of data-led inductivism that is running through much of social science…" Longley & Mesev, 2001:4*

The research proposed in this thesis attempts to ride this wave of data-led inductivism in order to assist in finding new and useful information about the urban areas in which we live. One of the major reasons for this slow development is indeed, that there has been a limited offering of useable data available (Longley & Mesev, 2001). This study makes use of newly created remotely sensed data in order to measure the intensity of land use within an urban environment, taking structural volume as a proxy for urban density. The concepts of urban density and structural volume are defined here, as well as some discussion into the fields of GIS technology and data acquisition as related to the proposed methodology.

2.1. The study of urban density

Urban studies in general have been traditionally focused on the two primary dimensions of space (i.e. location). However, the urban landscape is fundamentally defined by *three* physical dimensions. There is an opportunity to improve our tools for studying urban areas by taking the vertical dimension into account. Batty *et al* (2003: 11) have similar thoughts in saying that:

> *"…one of the major limitations of urban analysis has been our failure to embrace the third dimension for it is very clear that by restricting our analysis to two dimensions, information about the city is grossly simplified."*

Longley & Mesev (2001) observe that urban 'density' is a concept that is not well defined in urban geography. Urban density, in the context of this thesis, is the intensity of space taken up by the physical structures that make up the urban environment. That is, each building has a volume based on its surface area and height – the product of which is taken as a proxy for describing physical density. The aim here is to quantify this characteristic in order to be able to compare the city at different stages in time - and to compare different cities. The expectations for the results are broad and they are discussed in the following chapters. Simply stated, the results are expected to visually and statistically describe the chosen urban area in terms of its buildings and structures – their volume and density – by quantifying patterns and statistics. These results can be created for different periods in time to aid in the analysis of change. These visual results can then be compared to traditional urban pattern theory in order to test for validity.

It follows then, that this study falls into the realm of urban study and urban geography in general. Thus, some general background into urban geography is offered and the relevance of this study is put into context. Figure 2.1 shows how the chosen scale of study fits into the broader scales of geographical land use study.

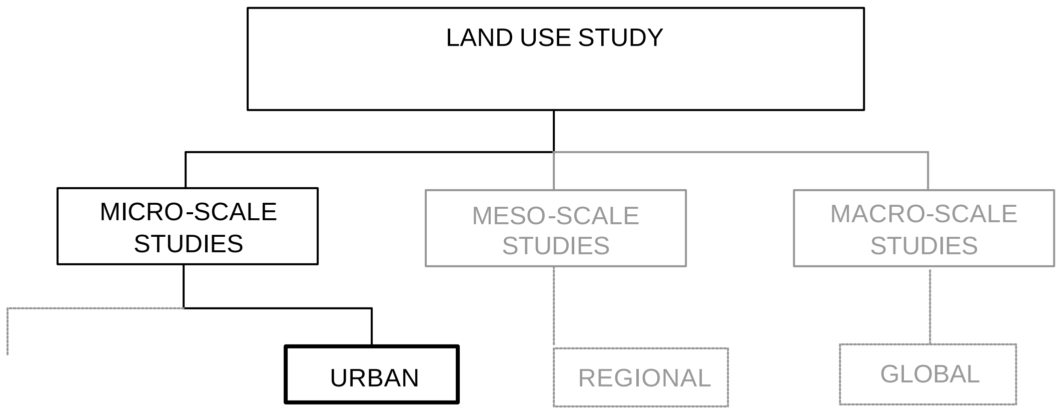


Figure 2.1. The position of urban study relative to other scales of geographical land use study.

2.1.1. *Urban geography*

> *"Urban geography studies the patterns and processes which occur between and within urban places; the objective form which these take, the subjective manner in which they are interpreted, and their mode of origin at both local and societal scales."* (Herbert & Thomas, 1997:4)

This definition of urban geography hints at its inherent diversity. Geographical study of urban areas is a broad and variable one. Its precise definition is dependant on the specific field of interest, which can range from marketing geography to transport geography – and is fundamentally dependant on the scale of observation (Pacione, 2001). Study at the urban scale demands investigation at detail levels of the highest possible order. Specific focus can be on topics such as urban population dynamics, the urban economy, housing and transport issues, etc. (Pacione, 2001). The aspect focused upon in this study is the physical spatial density of the urban area. All (urban) structures have, in their primary definition two dimensions – i.e. an attribute of location. With this fundamental fact, much information can be gathered and drawn from analyses applied to these spatial data and has been done in depth in the past – from the traditional work done on urban pattern and growth theories (e.g. von Thünen's work on the economic model of land values which decrease proportionally to distance from a central point) and economic pattern models of Hoyt and Burgess from the first half of the 20th century to modern studies of transport and network structures.

Following from the above Herbert & Thomas quote, the essence of urban geography is to identify patterns and processes existing within the urban environment and to study their characteristics. This is a question of space – where the patterns are, and how can they be found. Many models of urban patterns have been theorised and studied since the end of World War I. These models are based (more traditionally) on ecological models but also political economic based perspectives (Pacione, 2001). The proposed methodology attempts to replicate these result-types by using a physical-entity based approach.

2.1.2. *Urban study in The Netherlands*

Urban development in The Netherlands is diverse and is influenced by many role-players. Policy on urban development is conceptualised (in the west) on regional scale plans rather than local ones (van der Cammen, 1988). The Randstad area comprising the four major cities of Amsterdam, Rotterdam, Utrecht and The Hague, along with many smaller cities and towns make up this complex network of urban areas. It has been the objective of spatial planners in the Netherlands to create an interlinking metropolis based on functional relationships between these cities, while continuing to maintain a form of natural balance with agriculture and protected areas (van der Cammen, 1988). However broad the development objectives have been in this area, there have been significant localised plans implemented in specific cities. Amsterdam even has enough persuasive power to swing national legislation on spatial planning by leading by example (Faludi, 1991).

The effect of both these local and regional policies is evident in the spatial nature of the area today. The broad spectrum of interdependent, individual cities dictates its classification as a network city (or better in this case, urban conglomeration). The poly-nuclear nature of the area is dependant and influential on, among others, the transport infrastructure, functional interdependencies and residential needs of the individual municipalities (van der Cammen, 1988).

If one looks at the four major cities individually, new patterns of development and evidence of past policies can be seen. The northern area of the Randstad has the greatest dynamics and diversity, and its biggest issue is the provision of housing in a restricted development zone (VROM *et al*, 2004). As a result, the focus is on 'densification' and/or revitalisation of derelict industrial zones – it is envisioned that 40% of the housing requirements be met within *existing* urban areas (VROM *et al*, 2004). This implies a great increase in densities in the urban environments in the future and a way of assessing these future forecasts as well as past influences is required. The proposed methodology responds by offering a quantification of this characteristic and procedures of monitoring change in order to better understand the processes involved in real world implementations. More site-specific discussions into urban areas in the Randstad area of The Netherlands are offered elsewhere in this thesis.

2.1.3. *Urban density – current research*

Traditional urban study is focused on deciphering the volume/intensity of land use in the urban area by quantifying population, land use and functional diversity[1]. However, the method of measuring it has never been primarily focused on the physical characteristics of structures. In fact, Batty (2000) illustrates that, until now, urban geography has been dominated by small-scale piecemeal studies that revolve around aggregate theories of pattern description, individual behaviour and cultural theories. In later work he and his colleagues have offered some more derivative alternatives to the exploration of urban density. Batty *et al* (2003) propose this in their work, but remain mostly focused on functional density (i.e. diversity) rather than actual (physical) density. Also their scale of interest revolves around 'land parcels' which are homogenous groupings of land areas which cannot describe individual entities. Some of their methodologies of visualising and aggregating are congruous with the methodologies offered here, but since their underlying quantification is different then the results will (presumably) be different.

Further work into urban density has been carried out by Fisher-Gewirtzman (Fisher-Gewirtzman *et al*, 2003) which centres on his proposed 'Spatial Openness Index' which attempts to quantify the perceived density of built-up areas by measuring certain 3D visual cues. The primary aim of this research is to discover the quality of the urban environment based on human perception - and is calculated from a 'view point' outwards onto a variety of spatial configurations. This approach is highly technical and deals with many mathematical problems revolving around 3-dimensional topology and combines it with the human sciences of perception and psychology. Although this approach incorporates the physical characteristics of urban space, it does not attempt to quantify it, but rather quantify the *perception* thereof.

Another method being explored to define and measure the intensity of land use in an urban environment is the use of mail delivery points as an indicator of land use intensity. This approach investigated by Longley & Mesev (2001) is described as necessarily imperfect but useful none-the-less, due to its fine scale. Their focus on the importance of scale in the deduction of such indicators is important in this context as well – the use of even more highly detailed data makes some analysis possible that was never before feasible. However, much of the existing study into urban density is theoretically focused on a socio-economic perspective – describing gradients and change in terms of population, income, property values, etc (Batty *et al*, 2003). With these foci, studies have been made with aggregated data – at best, at the address-point scale[2]. Longley & Mesev (2001) point out that urban and regional settlement theory has been constrained by the quality of the data sources available. There is currently an opportunity to investigate these phenomena by applying a more specific, entity-centred approach based on physical characteristics – which can be accomplished by observing and analysing building volumes derived from highly detailed data, along with capabilities of GIS. With this new approach, a more holistic study of urban areas can be undertaken.

2.1.4. *Physical density*

What is noticeable from the above account of current practises is that there is very little focus on the simple physical characteristics of urban areas. Either the focus is abstract (Spatial Openness Index) or functional (land use diversity) in nature – however, neither of these approaches covers the aspect of pure physical properties. Current spatially-based land use models and land use descriptions (physical studies) forecast the category of each grid cell based on some theoretical background – be it, biological criteria, economic criteria, or multi-agent criteria (Walsh *et al*, 2004). All of these methodologies fail to incorporate the *intensity* of use in each of those cells. Longley & Mesev (2001) also point out the need to incorporate the intensity of land use into such studies. Their suggestion of using property taxes and number of storeys of buildings is comparable to the proposition made here and its importance can be described as follows: simple statistics provide land use measures for each category, but will not reflect the magnitude of use within each area. In table 2.1 assume that **A** is a commercial high rise building and **B** are small/low-rise residential areas. Statistically in table 2.1.a, the total pixel-area (influence) is described as 89% residential and 11% commercial. It is obvious that some measure of intensity is required to complement the simple 'flat' approach in order to emphasise (incorporate) the influence of the intrinsic density of the physical structures – especially the added influence of skyscrapers. Table 2.1(b) shows the *observed* effect of a higher intensity. In order to calculate these intensities, a measure of cell density is required. If, as proposed, height is used as a density indicator, then category **A** (with a height 10 times that of category **B**) will have a total pixel-area of 56% and category **B** only 44%. This simple premise is the basis on which this research is grounded.

a

B	**B**	**B**
B	**A**	**B**
B	**B**	**B**

b

B	**B**	**B**
B	**A**	**B**
B	**B**	**B**

Table 2.1. Visual description of the influence of intensity in grid based analyses.

2.1.5. *Proposed application*

The new data measuring technique proposed here will be used to create information that can assist in the general study of urban areas. One particular focus will be on the spatial pattern described by the urban volume layer. The results obtained will be compared to the theorised models of spatial structure for the areas concerned in the case studies. The basis for comparison will be the three classical models of urban structure namely, Burgess' concentric zone model; Hoyt's sector model; and Harris and Ullman's multiple-nuclei model (Pacione, 2001) – and, importantly, the more recently developed "edge-city" theory. These models originate from urban study in the USA, but have been adapted and used world-wide. The figure below (Figure 2.2) provides a graphical description of the three classic models that are to be considered. Figure 2.3 shows a manifestation of the edge-city theory, which describes its development around a 'ring-road' infrastructure.

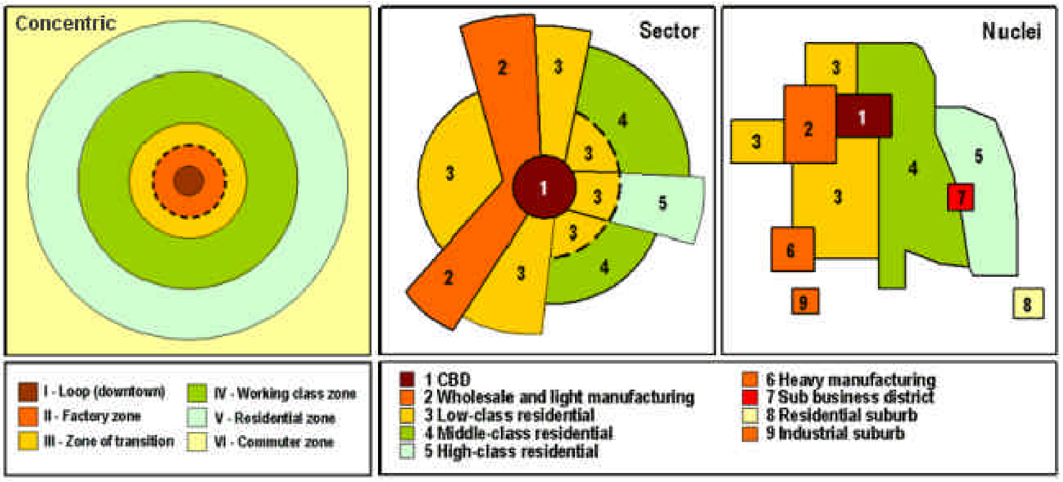


Figure 2.2. Three classical models of urban land use patterns. *Adapted from: Sanders, 2002.*

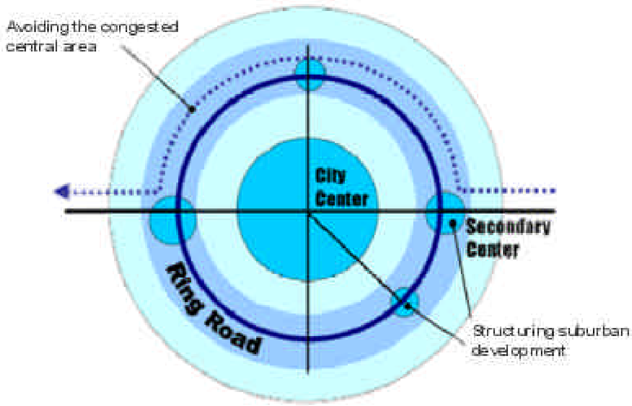


Figure 2.3. Theoretical view of the edge-city concept, built on the development of a ring-road. *Adapted from: Sanders, 2002.*

These three classical models are often gilded as too simplistic, but are continually used as a basis for consistent study practises. The purpose here is not to question or distinguish between different schools of thought, but rather to provide a new way of quantifying the spatial structure within the urban environment. The edge-city concept, again, originates from the USA and is based on the concept that new urban centres are formed around transport (i.e. freeway) nodes at the periphery of traditional central areas of the city. This more recent theory may be more applicable in the analyses performed further in this thesis.

Traditional testing of these hypothetical models is generally based on data that are either population or diversity centred – in fact Longley & Mesev (2001) argue that should a general rule be applied to the creation of urban inventories it should be based on the locations of households or human individuals. If this were true, then the major physical characteristics of the city are presumed irrelevant. The method proposed here offers a wider incorporation of the aspects that make up the urban environment at an infinitely finer scale. The inherent inefficiency of such population/diversity methods is that the scale is not accurate enough to depict the actual landscape of the city. It is important then, to offer a new and complementary way of studying urban density that can show the urban landscape in a way that is most recognisable to human perception and for this, high detail is imperative. Fisher-Gewirtzman *et al* (2003) agree that the approach to urban density should be through a morphological study – the results produced in this thesis can then be cross-evaluated with more traditional study methods that are based on other underlying theories.

The logic behind the proposed methodology is intuitive in its nature by virtue of basing the density calculations on the *intensity* of land use in the urban environment. This is akin to human perception of the urban habitat in which they live or work; and along with physical spatial configuration has a major influence on human perception (Fisher-Gewirtzman *et al*, 2003). It is argued here that this method is less abstract than measurements based on moving populations and intensity-oblivious diversity indices and as a result will be more intuitive to interpret and understand.

The purpose of studying urban geography is, again, extremely wide in scope. In the specific case of land use in an urban setting it is important to gain knowledge and explore these urban habitats so as to better understand their spatial and temporal patterns in the most descriptive way possible. With a solid analysis, these findings can be used as a *tool* to better the tasks of town and regional planning, service provision and social understanding on the part of local government (Longley & Mesev, 2001). They also point out that residential density is already seen as central to long term sustainability and planning within urban environments. This additional tool could assist in making these types of decisions more accurate. Another area of application not dealt with in this thesis is the use of building volumes to determine heating requirements (Neidhart & Brenner, 2003).

2.2. GIS and data

The significant role that data and technology have played in the development of regional and urban studies cannot be over-stressed. Without improvements in the tools, the science cannot progress (Longley & Mesev, 2001). Fortunately, there are some advances in GIS and digital data capture techniques that offer promising products that may assist in the development of these sciences.

2.2.1. *GIS trends*

The strengths of GIS to analyse spatial data are inherently useful in the field of urban study. It is pertinent to account for the current trends in this technology sector with regard to urban research methods. The ability of GIS to collate many sources of data and offer analysis capabilities for that data is profoundly useful in terms of any land use-related study. Apart from some 'non-spatially explicit' land use models, GIS can be applied to align disparate datasets, analyse and probe the data in whichever way the model dictates (Agarwal *et al*, 2002). As a result, much land use study makes use of GIS in some form or another – be it as a simple map viewer or more crucially in spatial analysis/prediction methods such as cellular automata (Agarwal *et al*, 2002) – (also see Schotten *et al*, 2001; Van der Merwe, 1997 for examples of using modern GIS techniques in land use related study). With this GIS underpinning, the advancement of the technology has potential to improve the science of urban land use study in the same way that computer advancement aids GIS in general (Batty, 2000).

Until recently most urban study with GIS has been focused on 2D geography – there are however many opportunities of expanding this field to include new data and analysis using three dimensions (Batty, 2000). This major progression toward 3D mapping and analysis is well founded in recent literature (Bhunu *et al*, 2002; Billen & Zlatanova, 2001; Kolbe & Gröger, 2003; Rahman & Khuan, 2003; Ramos, 2002) which is summarised by Shiode (2001). Already the capability of handling 2.5D data[3] is available through spatial data attributes; and Digital Elevation Models (DEMs) are widely used for varying purposes. Where visualisation is the primary concern, 2.5D data do suffice – however, in cases where analysis is to be carried out true 3D data are required. The realisation of fully capable 3D-GIS has been slow, but definite (see Kolbe & Gröger, 2003). With a continued need for 3D evaluation, a progression in the technology will surely follow. There are many applications that find 3D GIS/visualisation appealing – e.g. architecture, town-planning, land use modelling, etc. (Bhunu *et al*, 2002; Zlatanova & Tempfli, 2000). In the case of urban density discussed here, the use of true 3D modelling seems futuristic. The requirement for such abilities are also not yet developed and as a result the technology has been slow to forge ahead.

However slow the progression from 2D analysis to true 3D analysis is, the opportunities for basing 3D knowledge discovery on 2D data and traditional analysis are vast. The proposed study of urban densities requires only a manipulation of conventional methods. Such analysis is based on the "z-value" of the data – the 3D attribute that describes building volumes. The possibilities of performing such GIS tasks are well documented and are easily achievable in many popular desktop GIS software packages (ESRI's ArcView; Clarke Labs' Idrisi; etc.). These abilities are showcased in the case studies that follow in further chapters.

2.2.2. *GIS for Urban Study*

Fundamentally, any physical structure has a spatial description. GIS is a spatial tool box. At a simple level, it is then evident that the two disciplines are symbiotic. At an urban scale, GIS has been described as a "great tool for popularizing and deepening urban analysis" (Okunuki, 2001:181). It is this mutual ground in technology benefiting traditional study that holds much interest in current research (Walsh *et al*, 2004). This significant recent emergence of GIS in land use study, and urban study in particular, has brought about many application-specific modelling software systems used to study land use and its change (see Schotten *et al*, 2001 and Van der Merwe, 1997). This technological effect is so great it is almost impossible to imagine any land use study now, or in the future, that does not use GIS in some way.

A significant advantage of using GIS in land related study is its ability to measure change over time. This is especially appealing to the fields of land use change modelling, but is also applicable in a quasi quantitative study of the change in urban patterns over time (as is proposed here). Most desktop GIS packages offer the capability to quantify change in its magnitude and its location – a time-series analysis can simply be done and is demonstrated in the case studies here. All raster GIS' can decipher, at least, a grid subtraction which essentially shows where change has occurred between to raster images. Some dynamic visualisation techniques can also be used to assist in the change analysis.

Many traditional land use change theories focus on describing *why* land use changed rather than *where* it changed (Walsh *et al*, 2004), but focus now is upon gaining insight into the spatial characteristics of (urban) land use and its change/prediction. As the need for greater technology develops, GIS and 3D-GIS will need to provide the foundation for the exploration of urban change – and this has already been occurring for some years (see Köninger & Bartel, 1998). This thesis will continue to explore these opportunities in using GIS technology to better understand urban land use and its measurable characteristics.

2.2.3. *Current data breakthroughs*

A major drawback in the advancement of urban study has been the scarcity of data that are detailed enough to measure the concepts described in the adjoining theory (Longley & Mesev, 2001). Fortunately, in the recent past some significant improvements have been made in the realm of data capture. Initially, the development and improvement of satellite imagery has had great implications for studies related to land use and its change/monitoring (see Bockstael & Goetz, 2002; Cardille & Foley, 2002; and Roberts *et al*, 2003), but its most applicable scale has regional and global scopes. Even more recently the technology referred to as Laser Altimetry, or LiDAR has emerged (Batty, 2000). This technique of capturing instrument-ground distances from an airborne scanner (mounted on an aeroplane) has produced data that are highly accurate in their vertical measurement, but also an improvement in the density of sample points measured. The result is high density sampling with an extremely consistent variability in the readings. Tremendous improvements in data accuracy and precision have been made, and this new data are well suited for studies at an urban scale. A discussion into the data and its related collection methods is presented in the following chapters.

2.2.4. *Proposed research*

It has been mentioned that there exist many similarities and mutual benefits between GIS and urban study. Due to this symbiotic existence, many forms of applications and application areas have been discovered and exploited. The following chapter describes how a GIS based methodology attempts to accomplish this. As exciting as these prospects are, the research proposed in this thesis is bound to current (stable) technologies. Hence the use of new high detail 3D data can be used in a 2D GIS environment. However, some investigation into the use of 3D visualisation techniques is carried out. Some further discussion into the future possibilities of these emerging technologies in the same application field is offered in the final chapters of this thesis.

2.3. Summary

This chapter discusses the relevance of urban studies to this proposed study of urban density. Some light is shed on the use of GIS and current data acquisition trends in the discovery of such indicators. Definitions of the phrases urban density, urban volume, land use intensity are given in order to place the theoretical background of this study into context. From this initial background the thesis follows on by describing the method of measuring urban volume in terms of urban theory as well as from a technical perspective. Following this discussion, two case studies are presented to illustrate the theoretical proposal in a practical application.

NOTES

1 Functional diversity is described by Batty *et al* (2003) as the number of different activities or functions occurring at the same time in the same measurement unit – i.e. commerce, residence, etc. per land parcel.

2 The Address-Point^{TM} product is commercially marketed and offers precise coordinates of all business and domestic mail delivery points in Great Britain (Longley & Mesev, 2001) – and is also available in The Netherlands under the acronym *Adrescoördinaten Nederland – ACN,* from the Dutch Land Registry Office.

3 The essential difference between 2.5D and 3D data is that 2.5D data represent only 2D objects with a vertical attribute, whereas true 3D data make use of photo-realistic facades (realistic visualisation) and incorporate a form of 3D topology (Köninger & Bartel, 1998).

Chapter 3

Measuring Urban Density

This chapter provides the first discussion into the practical implementation of the proposed urban density indicator. With the theoretical backdrop provided in the previous chapters, the focus here is to provide an inclination into *what* the method is and *how* it is developed and implemented. The methodology revolves around two main issues namely, data (its acquisition and integration) and GIS (the method of implementation). In order to asses the quality and applicability of the proposed indicator, two case studies are investigated – the theoretical design of these case studies is introduced at the end of this chapter and is followed by dedicated chapters describing, in more detail, the implementation of the considered indicator and the acquired results.

3.1. The Indicator

In simple terms, the proposed urban density indicator quantifies the volume of physical urban structures. This measurement grades all structures according to volume – using height and surface area as the parameters – thus allowing for consistent and global measurements and comparisons. With this measurement tool, much information on the urban environment can be inferred, analysed and visualised. Primarily, the use of the indicator is to show the distribution of volumes across the urban space – i.e. the spatial patterns inherent in the intensity of land usage. It will attempt to highlight the areas of urban significance in terms of land use by taking their intensity as a proxy for density. Important information on the functioning of the city system can be inferred from these data such as the functional centre and urban pattern.

3.1.1. *Methodology*

The method to be followed can be described straightforwardly as a succession of map calculations and GIS functions using various data input layers – a schematic diagram of producing a volume layer is presented in the figure below (Figure 3.1). More specifically, the premise of the process is the integration of a high detail elevation data set that depicts heights of individual buildings, with supplementary data in the form of vector definition data as well as an inferred ground level layer. A series of GIS functions including overlays, extractions, queries, filters and calculations are performed in this sequence to arrive at a generic layer labelled 'urban volume'. A full description of the data sets and procedures are provided elsewhere in this chapter.

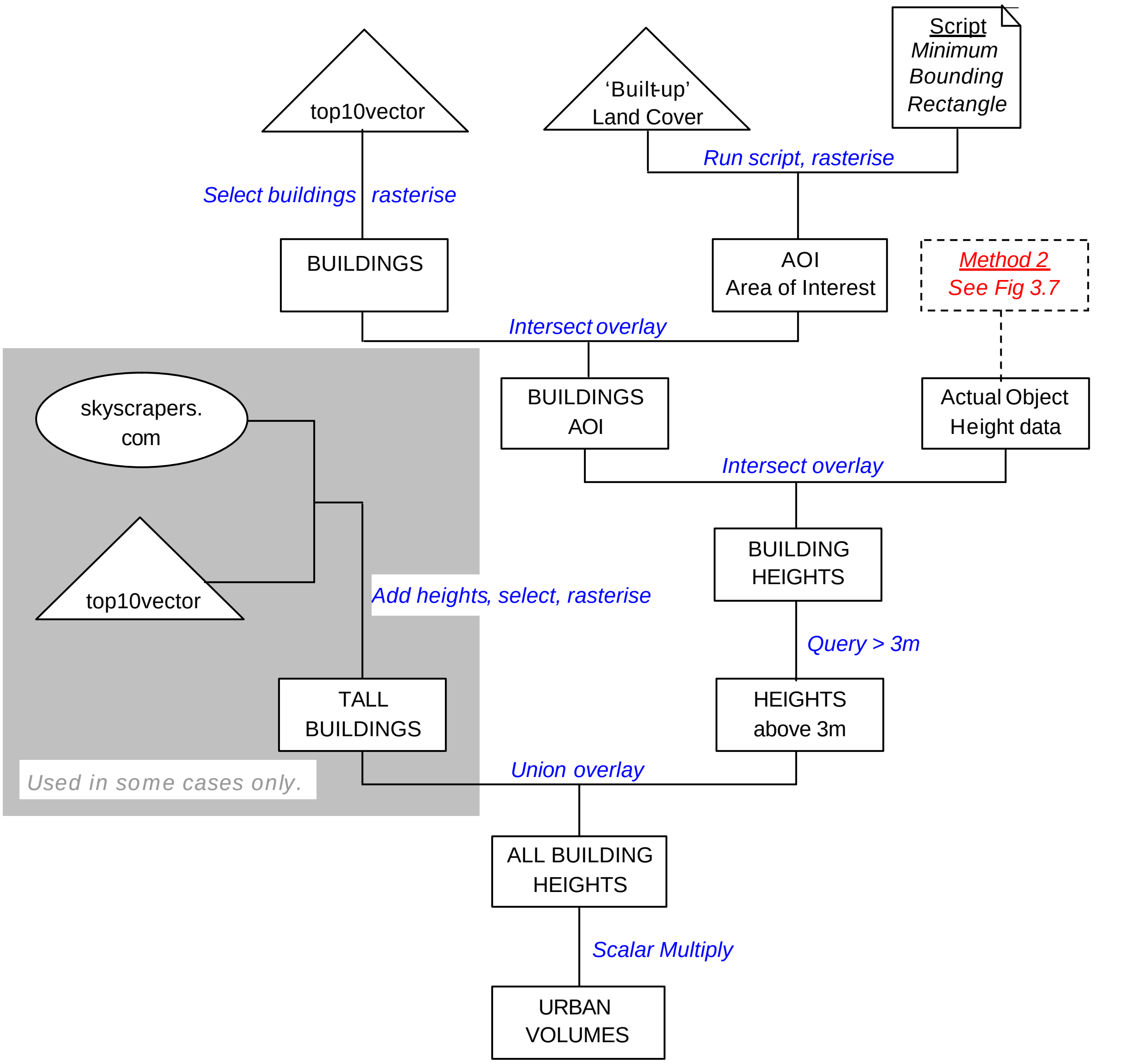


Figure 3.1. Cartographic flow diagram for the creation of the urban volume layer.

3.1.2. *Presenting the results – analysis*

From the calculated urban volume layer many methods of analysis can be used to describe the results. Firstly, the use of traditional 2D raster maps showing areas of high and low density provide information that is vital in determining the spatial urban patterns alluded to above. Additionally, some filtering processes can be applied in order to aggregate the fine resultant data into a more intuitive representation – some of these processes are used in the case studies that follow. Furthermore, flat maps are useful in comparison with existing maps of similar studies or comparative studies. Some statistical analysis can be carried out on this result layer by means of change analysis, histogram analysis as well as other common methods. 3D visualisation is also applicable to show the results in a more perceptive manner – thus making the visual interpretation more satisfactory.

3.2. Data Requirements

3.2.1 *Elevation data*

Central to the method introduced above is the use of elevation data to describe individual building heights. For this, a high detail laser altimetry data set is used. Laser altimetry height determination (commonly referred to as Light Detection and Ranging - *LiDAR*) is undertaken by the use of a laser scanner mounted on the underside of an aircraft. The aircraft flies along multiple predetermined flight strips, collecting laser pulse readings which represent distances and finally calculates heights. It performs these measurements by recording time/pulse differences of the laser signal with assistance from ultra-accurate clocks and uses differential GPS and an Inertial Navigation System (INS) to record the x,y location (MMS, 2001). The figure below (Figure 3.2) shows the position of the aircraft and the related readings and measurements it produces. For a full description of LiDAR technologies refer to MMS (2001).

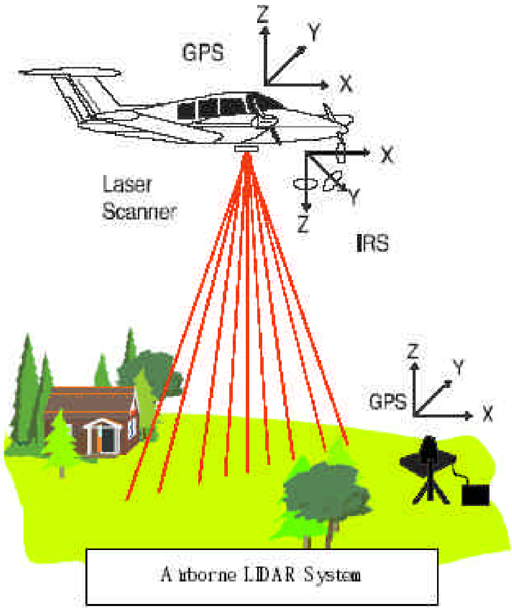


Figure 3.2. Diagrammatic depiction of an airborne laser scanning system.
Source: MMS, 2001.

These data are available in The Netherlands under the acronym, *AHN – Actueel Hoogtebestand Nederland,* which is initiated by collaboration between the local water boards, provinces and the "Rijkswaterstaat" (Ministry of Transport, Public Works and Water Management). This steering committee of the project has the task of coordinating the acquisition of these data from various commercial contractors and the processing of the raw data into error-checked grids ready for distribution to their clients (Crombaghs *et al*, 2001). The product they offer is an amalgamation of data collected by these multiple service providers that meet their accuracy and precision requirements. The dataset used in this thesis is a treated, commercially available 5x5 meter interpolated raster grid. It has an original point density of 1 per 16m2 and a height precision with a standard deviation of around 15cm (Van Heerd *et al*, 2000). The national data set is collected through many operators; the exact description of the filtering technique used for each of the different areas is retained by the commercial suppliers. However, one the known data treatment procedures applied in this process is the introduction of a heuristic algorithm to remove extremely high features in certain urban areas - i.e. buildings above ±45m in the Amsterdam area (Van Heerd *et al*, 2000) – which produces 'missing' data in some of the data sets. Therefore, a sub-procedure is introduced here to deal with this data anomaly in which high buildings are manually encoded from an external data source (discussed below) directly into the vector definition layer. These encoded values are then added to the original height data set and used further throughout the analyses.

As with all data sets, the AHN is subject to certain errors. The major errors present are errors per point; errors per GPS observation; errors per flight strip; and errors per strip block – a graphical representation of these errors can be found in the figure below (Figure 3.3) and a full description is offered by Crombaghs *et al* (2001). The AHN committee has undertaken much research into quantifying and minimising the effect of these errors and as such the data accuracy is required to be 5cm systematic error with a standard deviation of 15cm (Crombaghs *et al*, 2001). For the purposes of studying buildings with surface areas and heights in a scale of meters, this level of accuracy is deemed sufficient for the purposes of this research.

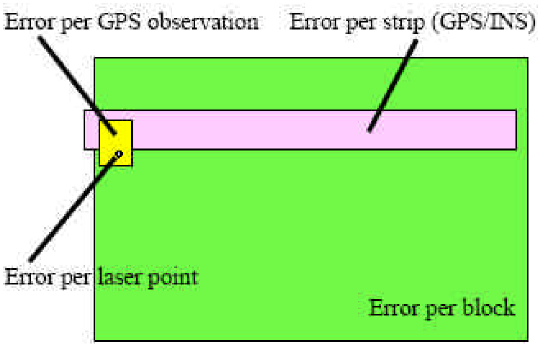


Figure 3.3. Different scaled error components. *Source: Crombaghs et al (2001).*

Another, less detailed issue with the accuracy of the height data is implied in its original use as a measurement tool for water height in *rural* areas. Also, due to the complex nature of heights in urban areas, the accuracy in these areas is substantially less. Evidence of this can be seen in the undulating values of 'supposedly' flat surfaces – see Figure 3.8.

Another characteristic of the AHN dataset is that the values are indicative of absolute height – the ground level itself is not intrinsically included in this data. The original data is measured in co-ordinance with the National Datum Level (NAP – 0m sea-level) which creates an object height discrepancy (error). Figure 3.4 shows how this effects the values that represent building heights. A procedure has been developed to counter this issue. A ground elevation level is derived from the original height data set. This surface is then subtracted from the original values and results in actual (true) object heights – eliminates the discrepancy.

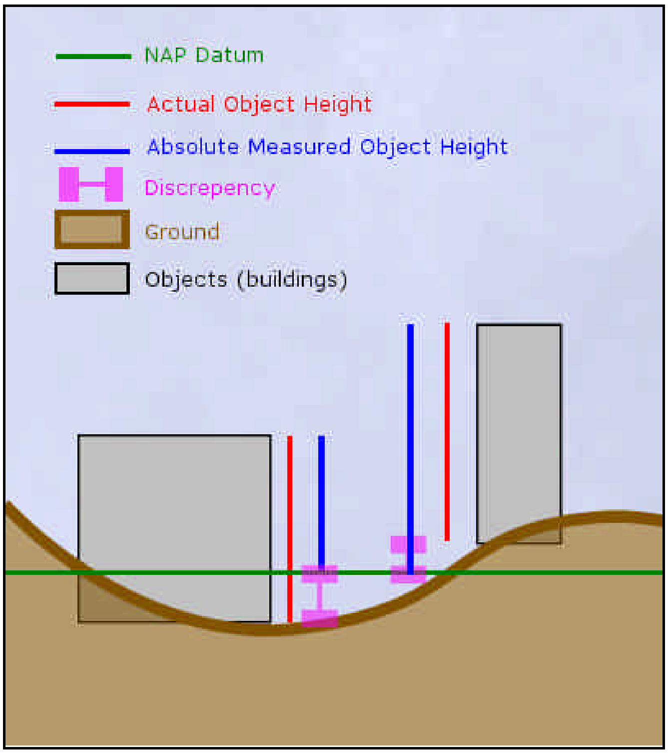


Figure 3.4. Exaggerated diagram showing the effect of ground level correction to the original height data in the applied methodology.

The surface layer is created using the original height data set. The procedure involves initially selecting the areas not defined as buildings (i.e. flat/ground-level objects) and using them as definitions to extract heights from the height layer. These values are then smoothed by applying a sequence of aggregation and filter techniques – see Figure 3.6 below - firstly, the data are generalised by lowering the spatial resolution using a minimum filter; this has the effect of extracting the lowest possible values of 100 m^2 areas. Secondly, these data are filtered using a 7x7 window and a Gaussian filter[1] to remove noise and smooth the data. Lastly, these data are aggregated back to a 5m grid for comparison with the other data sets, by using the mean of the grid cells.

In order to test the accuracy of this method, another (less detailed) data set of heights is used in a comparison. The outdated height data set (TOPhoogteMD), measured as a point per hectare from 1950 to 1990, is used for this comparison (geo-loket.nl). The TOPhoogteMD data set is only available in an interpolated grid and is thus not a fully accurate underlying surface model. Nevertheless, the values extracted from the grid – in the same manner as the proposed method – show a correlation of over 50% on a random selection of over 12000 points in the Amsterdam study area. However, it is noticeable from the scatterplot of these points (Figure 3.5) that many of the TOPhoogteMD values are significantly greater than 1m – and it is generally known that surface heights in Amsterdam rarely exceed this. As a further step, the TOPhoogteMD data values are queried for values less than the mean (0.18m) plus the standard deviation (2.9m). The correlation is again calculated with these selected values and a figure of 0.78 is now obtained. Thus, by taking values within one standard deviation of the sample mean (i.e. excluding positive outliers) a correlation of almost 80% is achieved. The deviation of this data is 1.7m which shows that the average difference between the two data sets is relatively minor. This amounts to a good method for creating the underlying surface model. Due to the coarseness of the TOPhoogteMD grid, the results may be inaccurate, but show positive signs for the method nonetheless.

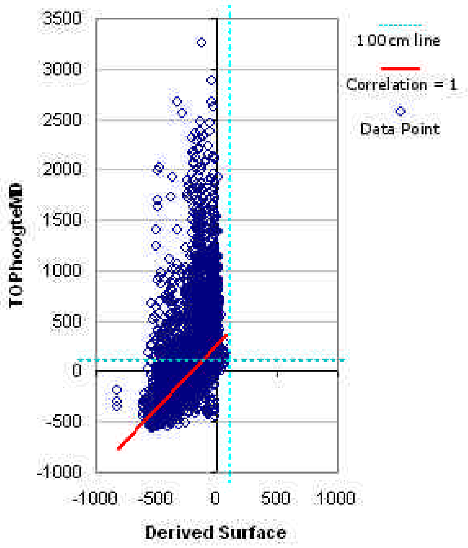


Figure 3.5. Scatterplot comparison of the derived surface heights and the TOPhoogteMD surface heights in cm. Data set of 12000+ samples.

Furthermore, a visual analysis provides clues to the overall spatial effectiveness of the method. The derived grid is visually similar to the underlying ground represented by some historical maps of the area. The figure below (Figure 3.6) shows the derived surface along with a map from the archives of the Amsterdam Historical Museum that shows the location of depressions prior to their 'filling-in'. The circles on the images show the areas of correlation. The surface derivation method described here is accepted to not be fully accurate – however, with a lack of any other data products for this purpose, it is used under the premise that the resultant 'actual object heights' can only be more accurate than the original 'absolute object heights' of the original AHN data set.

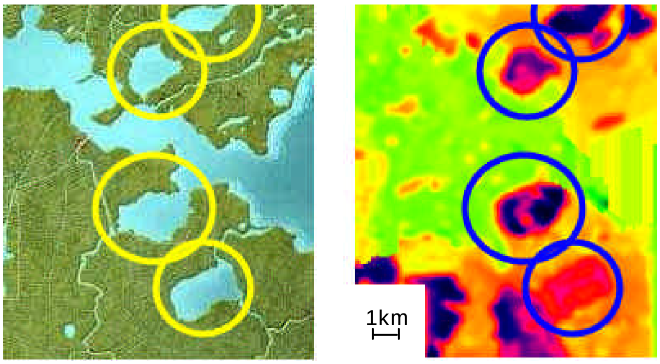


Figure 3.6. Highlighted areas of correlation between pre-urban (around 1200 AD) depressions and the derived surface model. *Adapted from: AHM, 2004.*

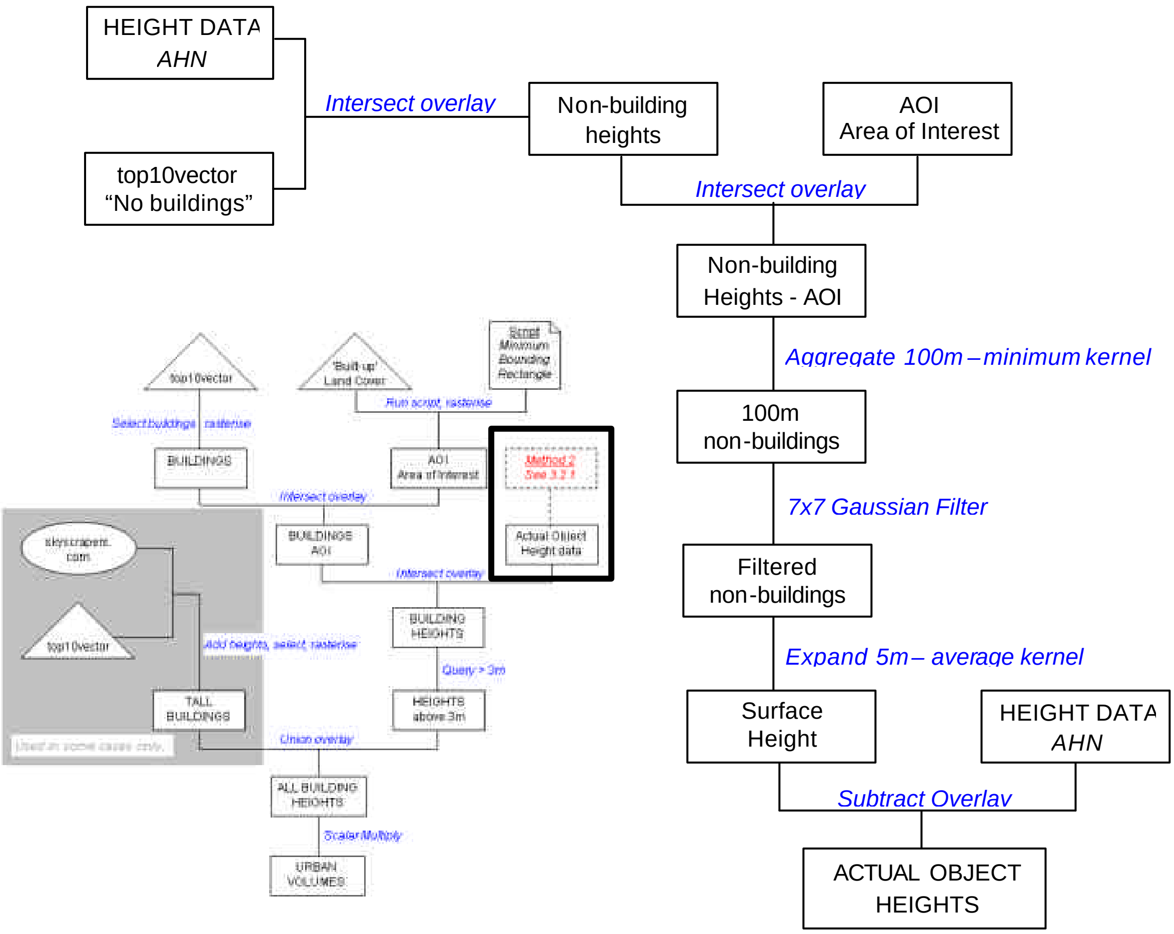


Figure 3.7. Elaborates on *method 2 from Figure 3.1*, the development of a ground surface layer – creating true building heights.

3.2.2. *Vector definition data*

Within the defined urban areas, it is important to describe the exact topology of the urban structures of interest. In order to do this, a topographical polygon vector file (top10vector) is coded into an integrated raster data layer and is then used as a mask to extract these structures from the original height dataset. This has the side-effect of removing all data not related to the physical structures in the urban environment. The data set however, has some limitations – most relevant is that the polygons representing these buildings are developed based on the external walls of structures only and contain no information on 'island polygons' within them. The figure below shows how the height data set shows island polygons that are not included in the vector layer (Figure 3.8). However, by retaining the original height data throughout the process, the effect of this inefficiency is excluded. In addition, the height data are further defined by running a low-value filter (< 3m) over the data in order to exclude the values found within in these 'islands' – i.e. trees, shrubs, cars, etc.

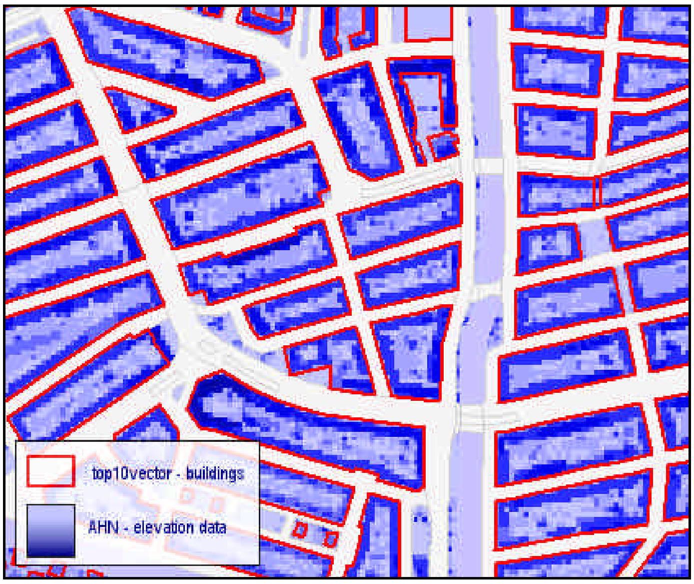


Figure 3.8. Example of top10vector inaccuracy – lack of island polygons.

3.2.3. *Further development of the data set*

Due to the exclusion of high values in some of the acquired data sets, an additional process is necessary to counter the effect of the filtering algorithms applied to the laser elevation data set. In response, a simple process of manual encoding is introduced. This is done by using an online database which documents all tall buildings in major cities across the globe. The database houses data on tall structures in more than 7000 cities – the data set contains fields of building names, heights/floors and year-of-completion (see Figure 3.9) – each of the records is linked with its specific location information (street addresses). In some cases, when structural height is absent, an average calculated value of 'height-per-floor' is multiplied with the number of floors to obtain a height value for that entity. The skyscrapers.com website is developed and maintained by the Emporis Corporation – which is advertised as the "world's largest resource on tall buildings" (skyscrapers.com). The data are publicly and commercially available – as with all data, they are susceptible to many types of error such as, bias or systematic errors. The company professes to adhere to internal data standards which maintain data that are comparable throughout the world – but the details of which are not publicly available. As a result, the error contained within this data is ignored and the data is used as is within this application.

	Building Name (Project Name)	Height	Floors	Year
1	Rembrandt Tower	150	36	1995
2	Mondriaantoren	123	32	2001
3	ABN AMRO World HQ	105	25	1999
4	Crystal Tower	95	28	2002
5	Breitner Center	95	23	2001
6	Oval Tower	94	25	2001
7	Belastingdienst	85	20	1993
8	Zuidoost Toren A	85	23	2000
9	IJ-Toren	80	20	2002
10	Zuidoost Toren B	80	19	2002
11	Overhoeks	80	17	1970

Figure 3.9. Example of skyscrapers.com data table for buildings in Amsterdam.
Source: skyscrapers.com.

The process used to manually encode the tall buildings is simple but laborious and repetitive in method – the online database is used to find the address of the structure; the address is found on a pre-existing map; the address is located in the corresponding entity (polygon) in the top10vector building polygon layer and the building height is assigned to the appropriate attribute of that feature. Figure 3.10 is a simple diagram outlining this iterative process. Finally, when all the listed buildings have been encoded, the vector file is rasterised and overlaid with the building height layer created separately – this sub-procedure can be observed in the flow diagram above (Figure 3.1).

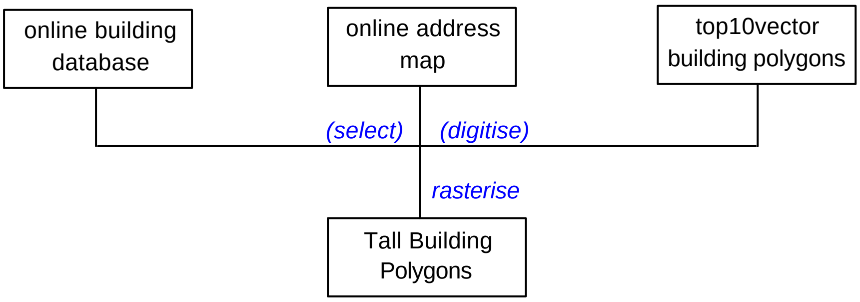


Figure 3.10. The process followed to manually encode high buildings.

The combination of these data manipulations results in a data set that represents buildings only with all high values included. The results are summarised in the clipped region shown in the figure below (Figure 3.11). The change represented as (a) shows the inclusion of new skyscraper building heights and (b) shows the effect feature selection, applied to remove non-building features.

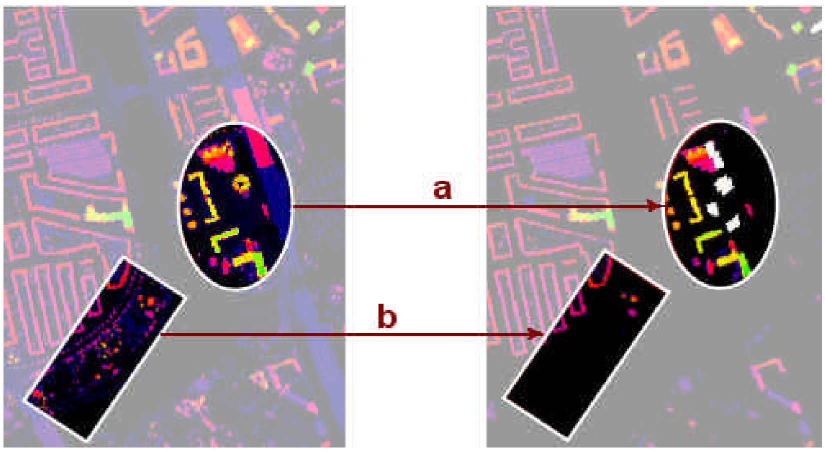


Figure 3.11. Snippet of the original data (left) and the treated data (right) showing – (a) the inclusion of high buildings in white and, (b) the extraction of building-only data.

3.3. GIS Implementation

The practical implementation of the proposed methodology involves some choices and issues concerning precise GIS analysis techniques and software packages used. Two primary GIS packages were chosen due to feasibility and availability – ESRI's ArcView and Clarke Labs' Idrisi.

3.3.1. *Raster vs. Vector*

A long term debate in general GIS discussion is that between raster and vector approaches. This argument was entertained in the choice of the final methods applied in this thesis. The two opposing ideas offer many pros and cons including accuracy, simplicity, file-size and many more. For the purposes of this thesis an informal test was carried out to determine the best combination for carrying out the methodology. In the first approach volumes were derived from vector-only data, by assigning grid values (heights) to the building polygon file and averaging the values over the surface area of the building. Some obvious issues arose, namely that only one value may stored per polygon (where in some cases, the polygon represents more than one building height) and that the polygons do not account for the “islands” that occur in the buildings in the areas tested (see Figure 3.8 above). A serious concern about the comparability of the values created also detracted from the appeal of the vector approach – no common basis is present to define the relation between the different volume values (i.e. volume per building?, volume per square meter?, etc.). Some of these general vector issues are highlighted in Figure 3.12.

In response to these issues, a primarily raster based approach was adopted – a major advantage is that the original data is retained throughout the process, with no averaging occurring. The accuracy of the raster data remains higher than the vector data because more values may be present per building entity. However more applicable the raster approach is for this methodology, there are some important accuracy and error issues related to its use. One of these is the issue of grid data accuracy. Figure 3.13 shows how raster data may either be lost or gained through the process of conversion – the offset of the two problems and the scale of the issue (i.e. < 5m^2 per issue) allow the accuracy levels of the study to remain acceptable. This occurs when the top10vector data are rasterised. Throughout the process a grid size of 5x5m is used and is aggregated only in the final step to aid in the visual analysis – because of this high spatial resolution the accuracy levels remain relatively high. In practical terms, the raster derived data are ready for analysis through use of filters, histograms, etc. without the need for later conversion.

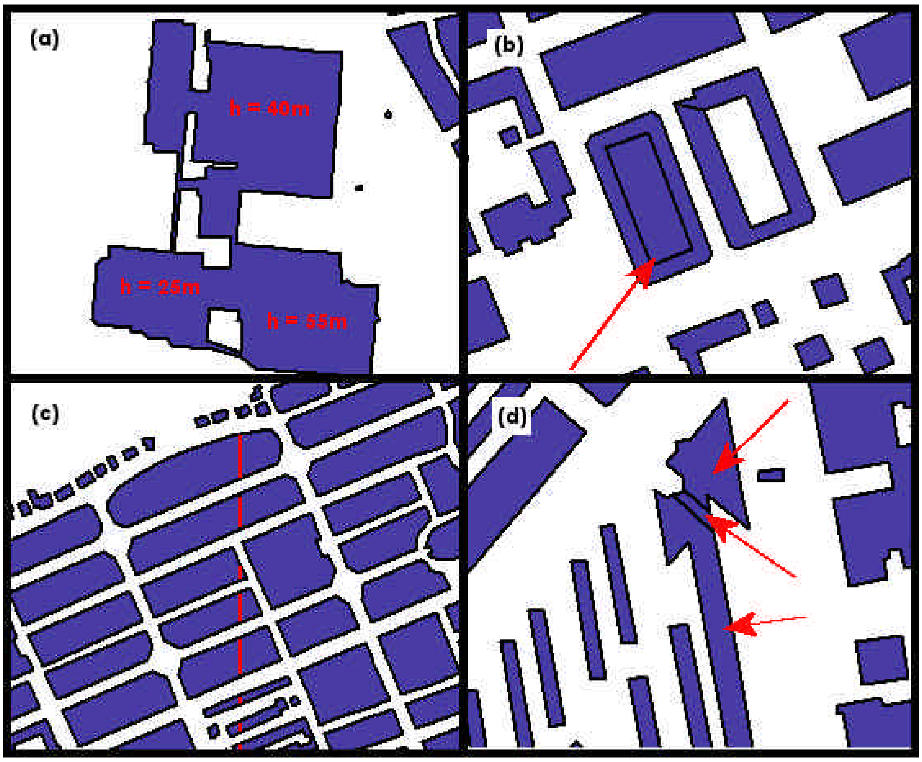


Figure 3.12. Some of the vector-related errors of the top10vector data set. (a) Single polygon with multiple heights; (b) included island polygons; (c) split polygons; (d) complex polygons. *Source: top10vector.*

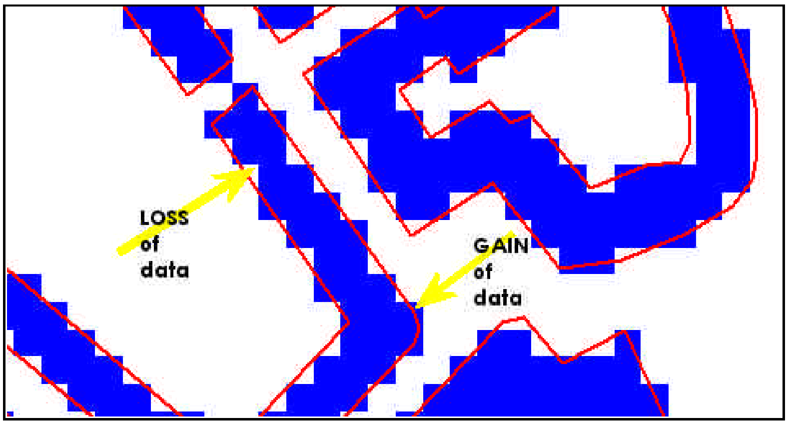


Figure 3.13. Inaccuracy of conversion from vector to raster data.

3.3.2. *General accuracy*

Error is inherent in all the methods, procedures and data used throughout the methodology. This error influence is present in all geodata applications, and certain limitations of accuracy and precision are observed. Influenced on accuracy levels are present in many stages of the methodology: initially the original datasets have some error which has been discussed in section 3.2. Additionally, the propagation of such errors continues through each GIS function applied. For instance, the process of converting vector data to raster data requires some method of aggregation – i.e. the original polygons are 'fitted' to a regular 5 x 5 meter grid and some data are lost. Any errors present in the early stages of the process are then propagated throughout the methodology and will create results that are continually less accurate. In order to maintain as high as possible standards, the original data error is minimised by maintaining the original resolution and thus propagation has a minimal effect. Continual error checking/validation and metadata creation help in correcting and documenting problems with the data which assist in creating a final accuracy estimation. Due to the comparative nature of this technique of evaluating densities, the effect of these errors is assumed to be minimal – each data set used in the analysis is created using the same method.

3.4. Implementing the Methodology

The range of application possibilities is vast for the urban volume layer. The focus of use in this thesis is for studying the spatial patterns and characteristics of urban areas by considering changes over time and space – this is a study of urban development, urban structure and an investigation into the processes that influence change. Although there are other application fields (see discussion in Chapter 2), the focus here on the spatial structure in the urban environment has value directly in both urban pattern studies and urban planning methods. As a way of testing the usefulness of the methodology, it is implemented in two case studies. Both of these studies focus on the urban characteristics of the major cities in the Randstad region in the western Netherlands. The theoretical definition of these urban areas has been discussed in the previous chapter; however some considerations must be made in defining the spatial area to be investigated in practical terms.

3.4.1. *Urban areas*

The practical solution used to determine the urban 'Area of Interest' (AOI) is described here and is based on the available data sets. The process is two-fold: initially, the map sheets are chosen by combining the definition of built-up land use (from the Dutch National Land Cover data set – LGN) and the polygon boundaries of municipalities (see Appendix A). Once these map sheets are chosen, a script is used to create the minimum bounding rectangle around the intersection of the municipal boundary and 'built-up' polygons. The script works by creating a rectangle that has the minimal dimensions around the built-up areas that are within the municipality and the code may be seen in Appendix B. The end result is a binary raster grid that defines the Area of Interest which is applied to all the subsequent data sets that are used in the methodology. A direct advantage of using this rectangular approach is the exclusion of the arbitrary nature of the municipal boundaries. The diagrammatic representation of this process can be seen at the top of Figure 3.1 above and the resulting AOIs can be seen in Appendix A.

3.4.2. *Investigating time*

The first application to test the developed urban volume methodology using the above described urban area definition, attempts to visually and statistically describe and analyse the change in urban volume over a period of 100 years. The chosen urban area is the city of Amsterdam in The Netherlands. The goal of this practical exercise is to obtain information on where and when the significance of certain areas of the city has changed. Results describe the locations and magnitude-of-change of densities within this urban environment. Focus remains on the density of development, with the spatial context used in descriptive terms only. The results are then compared with the traditional views and models of change in this same area – effectively testing both these historical ideals as well as the implemented methodology.

3.4.3. *Investigating space*

The second test case for the urban volume data is to create a similar data layer for multiple urban areas in order to test its ability for comparing urban densities between these different zones. The sites used are the four major cities of the Randstad region of the western Netherlands. The primary goal is to test the applicability of the measure to such a study and to find (if possible) where and how the cities differ from each other in terms of their spatial patterns and densities.

3.5. Summary

Proposed here is a practical methodology of describing urban density. The method is based on the use of building volume to quantify density of physical structures in urban space. The process is defined in a cartographical work-flow diagram that defines data and operations required to create the desired outcome. The practical essence of the indicator is dependant on some data sets that have within them some inherent inaccuracy and error. Some methods for dealing with or justifying these errors are used. Two applications have been defined in order to test the capabilities of this indicator and its methodology – these will be discussed in full in the following two chapters.

Notes

1. A Gaussian filter can be described as a 2-D convolution operator which works in a similar fashion to a mean filter, but uses a different kernel (window) that represents the shape of a Gaussian distribution. The isotropic (circularly symmetric) Gaussian follows this equation:

$$G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

where: σ = standard deviation

The resulting kernel used in Idrisi 32® has the following form:

0	1	2	2	2	1	0
1	2	5	6	5	2	1
2	5	8	11	8	5	2
2	6	11	12	11	6	2
2	5	8	11	8	5	2
1	2	5	6	5	2	1
0	1	2	2	2	1	0

(each value as a factor of 192: e.g. 5/192)

Chapter 4

Densities over Time: *Changes in Amsterdam*

The city of Amsterdam provides an interesting setting for examining both the applicability of the proposed urban density methodology as well as the analyses and results it may raise. The famous city offers characteristics that are useful in determining the value of the methodology – it is an old city with its beginnings around 1200 AD, containing a well established blend of medium height buildings in the protective environment of the old centre and the addition of modern skyscrapers around the periphery of the old city, mainly along the recently built ‘ring-road’ and other transport networks. This case study will attempt to discover how and where changes in this urban landscape have occurred during the 20th century and quantify them. It will divulge details on the pattern of density, statistical results of movement and provide some general insight into the metamorphosis of volumes in this dynamic urban area.

4.1. Background

From the early formation of the “residential law” (woningwet) in the very beginning of the 20th century, there has been a progression of initiatives to steer the growth of Amsterdam in the way best befitting the views of the community and local governments in charge (Hellinga & de Ruijter, 1985). From an early perspective on an industrialised process, the focus of Dutch regional and national planning has since revolved around ideas of sustainability and specialised spatial arrangements (Faludi, 1991). The continual application of development plans – the First, Second, Third and Fourth National Physical Planning Reports – have shaped urban areas in the Netherlands, with the power interchanging between local, regional and national levels. The main reason for the creation of planning on a regional and national level was the fear that the trends of ‘ribbon development’ and ‘dispersed pattern growth’ would have a chaotic effect on spatial development (Postuma, 1991). The city of Amsterdam had employed a successful autonomous plan prior to the national objectives, but even after the implementation of the national planning doctrine, the city ultimately wields enough power to steer regional and national policy by its own actions (Faludi, 1991).

The first effective use of the local expansion plan was that of the Amsterdam-South area, earmarked for residential use in order to cope with the rising population size. This beginning of the century plan formed the basis of urban expansion in the first 20 years of the 1900's. During the 1920's the garden-city commission (Tuinstadcommissie) was formed with the mandate to engineer some garden towns outside of the city limits (Hellinga & de Ruijter, 1985). Many more departments were summoned or formed during the period up to 1935 with the general objective of redefining the spatial extent of the city in order to cope with the increasing population and societal needs of the inhabitants in a sustainable manner. Research was carried out by the City Development Department (afdeling Stadsontwikkeling) into the best options in terms of the required expansion (Hellinga & de Ruijter, 1985). Most of the work completed in the 1900-1930 period was focused on the South and West periphery of the city – with the addition of the plans for the creation of the external garden cities. In 1935 plans were approved for the General Expansion Plan of Amsterdam (Het Algemeen Uitbreidingsplan van Amsterdam – AUP). It is clear that the AUP has had a wide-ranging effect on the spatial pattern of the modern city – and also its development in the 3rd dimension – even although its initial time scale of multiple decades was cutback due to early completion after only 20 years. The two major focal areas of the AUP were the Buitenveldert area in the South and the areas of Slotermeer, Geuzenveld, Slotervaart and Osdorp in the West (Hellinga & de Ruijter, 1985) – see Figure 4.1.

Figure 4.1. The General Extension Plan of Amsterdam in 1935. Names of the red-coloured major areas of expansion are in black. *Adapted from: Atlas Amsterdam, 1999.*

The plan also specified the approved density of dwellings per hectare – within the ring railway a density of 110 dwellings/ha was prescribed and outside of it, 70 in the west and 55 in the south (Hellinga & de Ruijter, 1985). Due to the interdiction of World War II, the AUP did not fully accomplish what was needed and some complementary plans were formulated to compensate – most notably, the development of the Amsterdam-North area in the mid 1950's (Van Der Heiden & Wallagh, 1991). After much consultation with national authorities, the city of Amsterdam acquired the South-East area of the Bijlmermeer for urban development in the mid 1960's (Van Der Heiden & Wallagh, 1991). These ideas were all indicative of the municipal outlook for the development of a 'lobe-city', which may be the inspiration for a poly-nuclear city today – their strategy to deconcentrate the concentration to other less densely populated areas. After a series of reconsiderations, the focus turned to the concept of the 'compact-city' (Faludi, 1991). This essentially defines an increase in density within existing areas of the inner city – mainly confined to the harbour areas along the IJ River. This change in dynamics in the 1980's reflects the rehabilitation of approximately 1400 hectares nationwide in The Netherlands (Faludi, 1991).

4.2. Hypothesis

The above discussion on the planning and dynamics of the Amsterdam urban area provides insight into the changes over the past century – the case study correlates some of these theoretical observations through the use of the newly developed urban density measure. The major periods of change in terms of space and intensity described above will be sought in the results obtained from the study. The initial spreading of the city into south, north, west and then the far south east in the first three quarters of the century should be captured by the analysis. In the same token the newly adopted compact-city approach's effect on intensity of use in existing areas should be noticeable. The development of the 'lobe-cities' in and around the newly (±1990) completed ring-road should be reflected as some high-intensity land use areas that develop in and around the 1980's and 1990's.

The expected outcomes of this case study are the successful presentation and accounting of urban pattern and urban pattern growth of the previous 100 years, in terms of density. These outcomes should be comparable to the theories and observations mentioned in the previous subsection. The results should specify density in the urban context, both by means of visual interpretation as well as numerical statistics. The outcomes should show these calculated indicators in terms of their change at each time interval of 10 years.

The results should be observable in 1D, 2D, and 3D visualisations and quantifications – all in terms of the time dimension. Graphs and tabular results represent the growth in urban density over the 100 year time-span. Traditional maps are used to show the areas that are affected by this increase. Finally, a 3D visualisation creates the most representative result that will show the expected increase in density, its location as well as it magnitude.

4.3. Implementation

In order to apply the generic model described in Chapter 3 to the specific temporal study of the city of Amsterdam, some extensions were developed and applied. The major addition is the development of data layers describing the building *location* for each decade from 1900 to 2000. For this, a specific data set was acquired from the Amsterdam municipality that details the construction-year of each individual building within the Amsterdam municipal boundary. A description of the process of further developing this set into urban density layers for each time period is shown in Figure 4.2 below. This dataset is used, with knowledge of some limitations – most notable is that the layer contains only a single date per building (the most recent construction). Essentially this means that the dataset may introduce some underestimation of volume due to the possibility that a building is constructed over an older one – which will thus no longer be included in the earlier date maps. Conversely, there is possibility of overestimation by the calculation of an older building with that of a new derived volume – mainly in isolated areas.

A secondary issue with the use of the data is its conversion from point vector data to a grid layer. In this process the values are aggregated to a 50x50 meter grid that represents only one date per pixel – the original data may also contain multiple dates for one individual building polygon (the point data set has a higher resolution than that of the building polygon data set). This represents a lowering of the overall accuracy of the method. The occurrence of these errors has been visually tested and the results are perceived as minimal; the drawbacks are not seen as serious constraints to the exploratory nature of the case study.

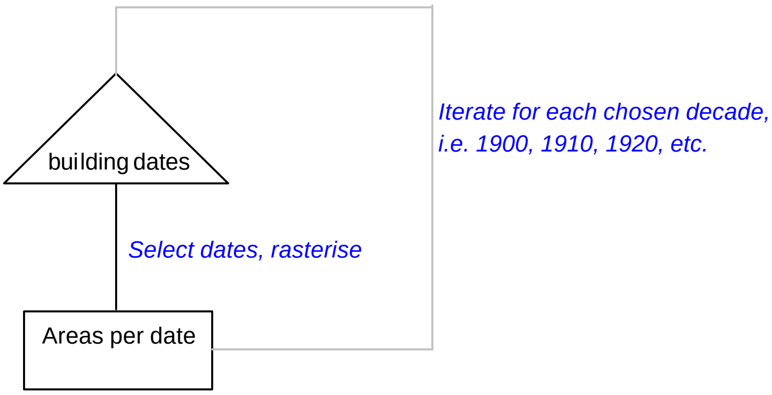


Figure 4.2. Flow diagram of the creation method for developing temporal definition layers for each decade.

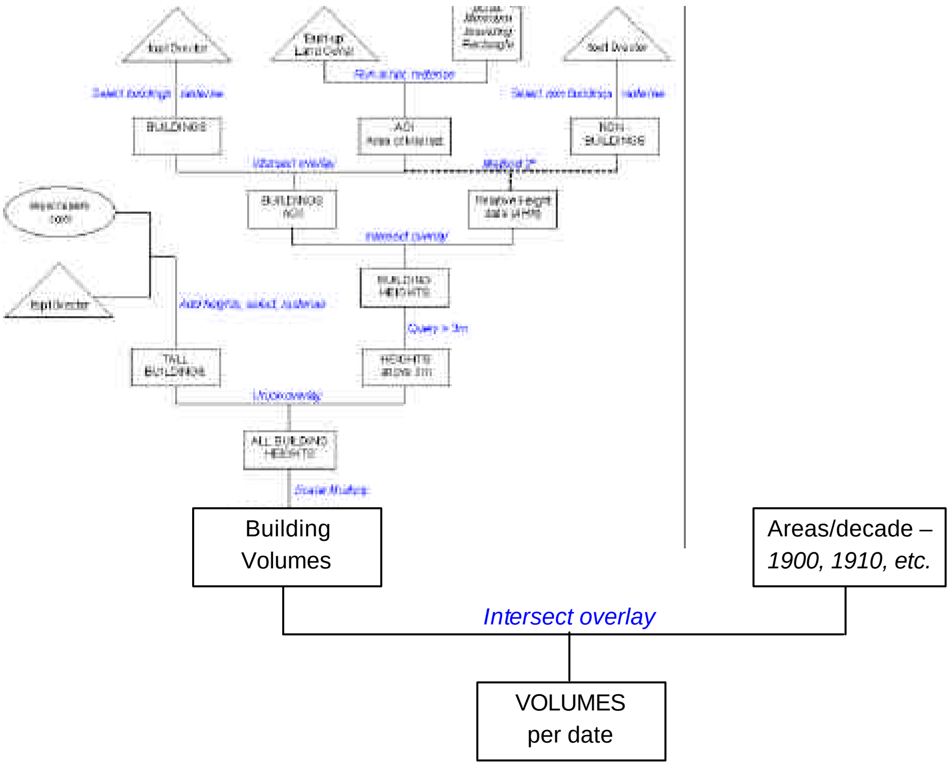


Figure 4.3. Amalgamation of the urban volume layer (Chapter 3) with the various date definition layers – the creation of urban volume data for each time period.

This additional set of data layers is then added to the generic urban volume method and the full analysis is carried out using two proprietary desktop GISoftware packages – ESRI's ArcView 3.3 and Clark Labs' Idrisi 32. Figure 4.3 details the overall procedure used.

4.4. Results

The set of Amsterdam urban volume layers provide the basis for number of analyses that are successful in terms of the prescribed hypothesis and outlined goals of this case study. Various methods are applied in order to accomplish these different tasks. Some different approaches were applied in order to quantify and analyse the change observed and are each discussed individually below:

- Numbers/statistics: *histogram, total volume*
- Maps: *time-series, intensity-pattern analysis*
- Vectors: *gravitational centre*
- 3D visualisation

Change – in Numbers

The results obtained from the different analysis perspectives require individual discussion. Hence, each individual output is discussed separately under the named sub-headings. Initially a statistical examination of the data was carried out. The graph below (Figure 4.4) depicts the change in surface area covered by certain building heights in 1900 and 2000. The outcome shows solid evidence of the increase in both horizontal and vertical dimensions – i.e. there are more buildings, and they reach greater vertical heights. These results are congruent with the general expansion theories discussed above.

A method of quantifying the change in density through the decades is to calculate and compare the 'total volume' of each period – i.e. the density indicator. This 'total volume' is created by summing the product of the building volumes and their frequency – i.e. it produces a value that describes the total volume of all buildings within the chosen area. The table below (Table 4.1) shows these changes. From the presented values it is possible to ascertain that major increases (percentage change compared to the previous decade) in urban volume occurred in, primarily, the 1920's, 50's and 60's with a steady increase during the last 3 decades of the century. This is indicative of the plans outlined in the above discussion – highlighting the general extension plans, garden suburbs and the latter expansions to the South-East, North and West. Also, well highlighted is the effect that World War II had on the development progression in the city, by the low value in the 1940's. The graph (Figure 4.5) shows how these changes develop (blue line) along with the cumulative increase of the total volume (red line). The blue line makes clear when the major development fluctuations were experienced in Amsterdam.

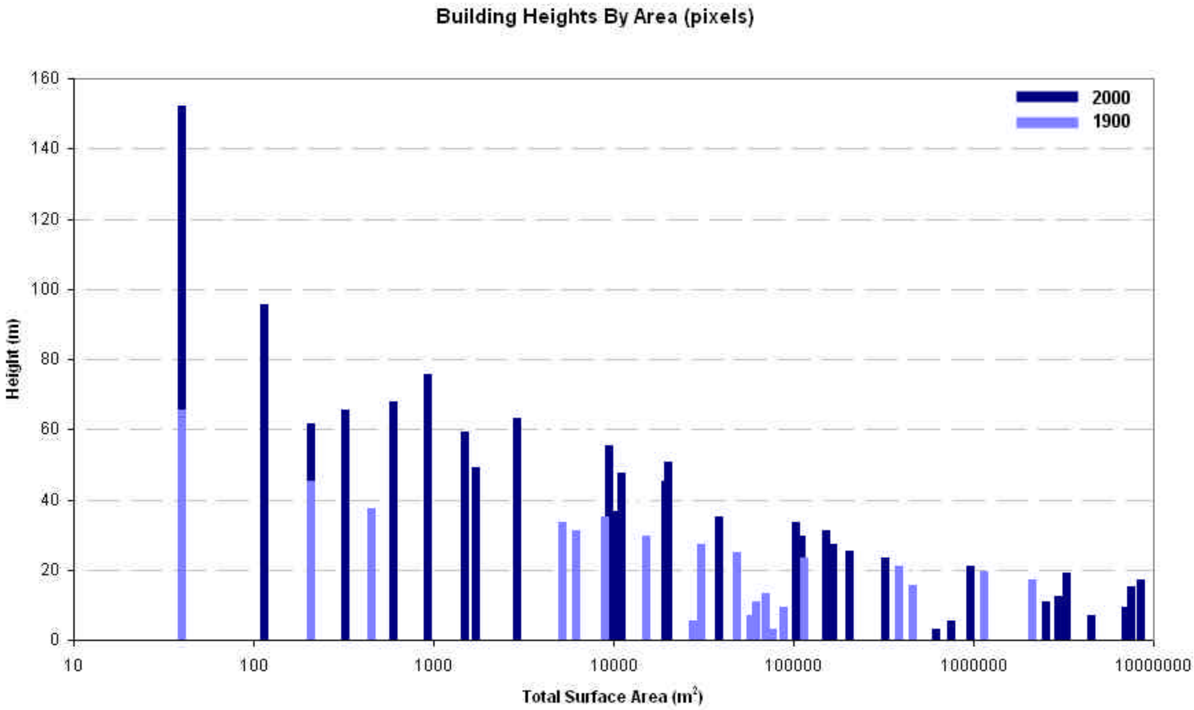


Figure 4.4. Histogram of the surface area covered by the various building heights in Amsterdam.

Year	Total Volume	% Change
< 1900	*1915369*	**-**
1900 - 1910	*2103018*	**9.8**
1910 - 1920	*2391517*	**13.7**
1920 - 1930	*3116965*	**30.3**
1930 - 1940	*3594963*	**15.3**
1940 - 1950	*3673413*	**2.2**
1950 - 1960	*4399810*	**19.8**
1960 - 1970	*5338256*	**21.3**
1970 - 1980	*5986879*	**12.2**
1980 - 1990	*6792976*	**13.5**
1990 - 2000	*7516748*	**10.7**

Table 4.1. Total volumes and percentage change in Amsterdam for each decade in the 20th century.

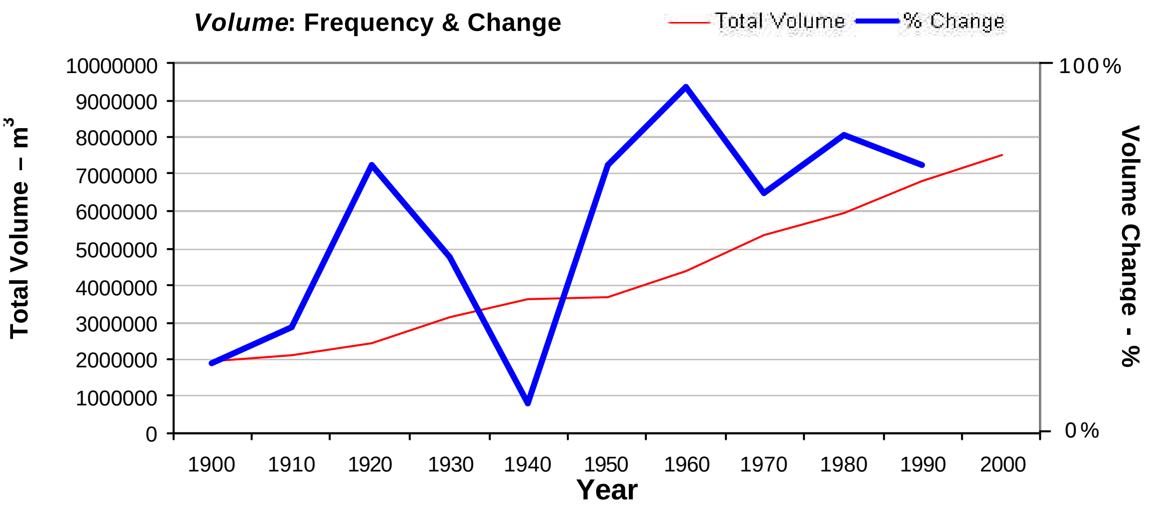


Figure 4.5. Table and graph showing total- and the change in- density between each decade.

Change – in Maps

The most traditional means of analysing the volume data created is through the use of conventional 'flat-maps'. The sequence of maps displayed in Figure 4.6 show the gradual changes in the shape of Amsterdam from 1900 to 2000 – in a time series analysis based on the city's volume. An animation of this change has been developed and is included in the accompanying cd-rom (*MSc CD:* "TimeAnimation")[1]. With this animation it is possible to observe the effect of the major strategies employed by the authorities on urban development – initially, in the first 60/70 years there is little change in the densities, but rather in the spatial extent of the city (concentration – deconcentration plan); in the following years the horizontal extension is halted and there is an increase in intensity in some areas (compact city concept).

From the diagrams in Figure 4.6 some more specific conclusions can be drawn on the growth of the city. Up until 1960 the spread of the city is seen to be generally circular, of low or medium density – i.e. the appearance of red colours are absent. This was proposed in the discussion above of the plans and policies of the urban area concerned. Firstly, the development on the outskirts of the old city – the south and the west are noticed. In the 1960's the suburbs in the west become noticeable (Osdorp, Bos en Lommer, etc.) and the initiation of the lobe-city plan is evident in the far south east (Bijlmermeer) in the 1970's. The 1970's and 1980's also show evidence of the planned creation of new outer suburbs of Buitenveldert and Amsterdam-North. Finally, the maps show evidence of the creation of the ring road in the 1980's and its effect on density. The renewal of previously lower density (green/yellow) areas into high (red) areas is noticeable. The South-axis area (around the ring-road in the south) shows evidence of the development of a planned high intensity land use zone. Also noticeable are the developments in the West and South East around the Amsterdam ArenA (area of De Entrée) in the latter decades of the century. All through the first 70 years, the density of the centre remains relatively constant, until the implementation of the urban renewal (compact-city) initiative – the results of which are noticeable in the deepening of the red colour in the traditional centre of the city from the 1980s onward.

It would be a point for further analysis to extend this methodology to be used in future forecasting. Ideally, to estimate the effect of planned/proposed developments in the next 10 years – which may help planners in determining the effect of the proposals. The basis for such an analysis is available through the use of detailed building plans (e.g. south-axis development plan); the 'New Map of The Netherlands' (the national development sketch for 2030); and the self-same online resource (skyscrapers.com) used elsewhere in the methodology.

Intensity-Pattern

The data created in this case study can be used to help discover the exhibited pattern characteristics of Amsterdam. The urban volume layer is further processed in order to assist in this. An independent additional method is offered. It utilizes two steps – firstly the data resolution is reduced to 500m (per grid cell) using a maximum filter and secondly, values above 3 standard deviations are selected (thus the extreme values only). The figure below (Figure 4.7) shows the results of this analysis. It can be clearly seen from the image that the city has many high density areas outside of the traditional centre. This is strong evidence of the multi-centred nature of the city. It is also noticeable that these 'edge-cities' are generally confined to the ring road and in some homogenous groups (i.e. West, South and South-East). This method of defining a city's pattern based on densities is complementary to the traditional methods based on population, transport, etc. It takes into account the value of weights based on the height of buildings and thus creates a more holistic view of the city that is focused on the intensity of use and its effect on the urban landscape.

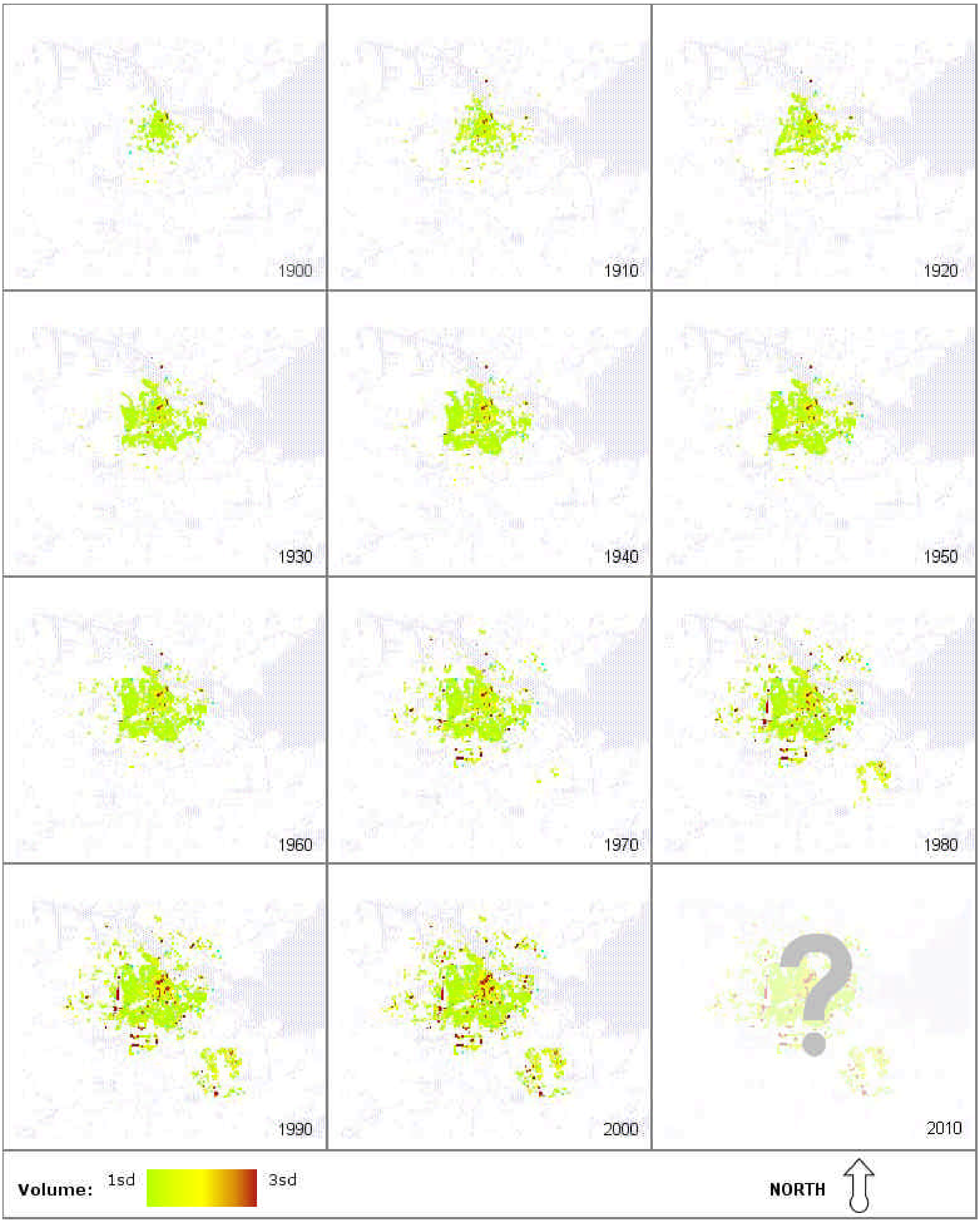


Figure 4.6. Change in urban density in Amsterdam over a 100 year period. Values show gradual change from the mean to three standard deviations.

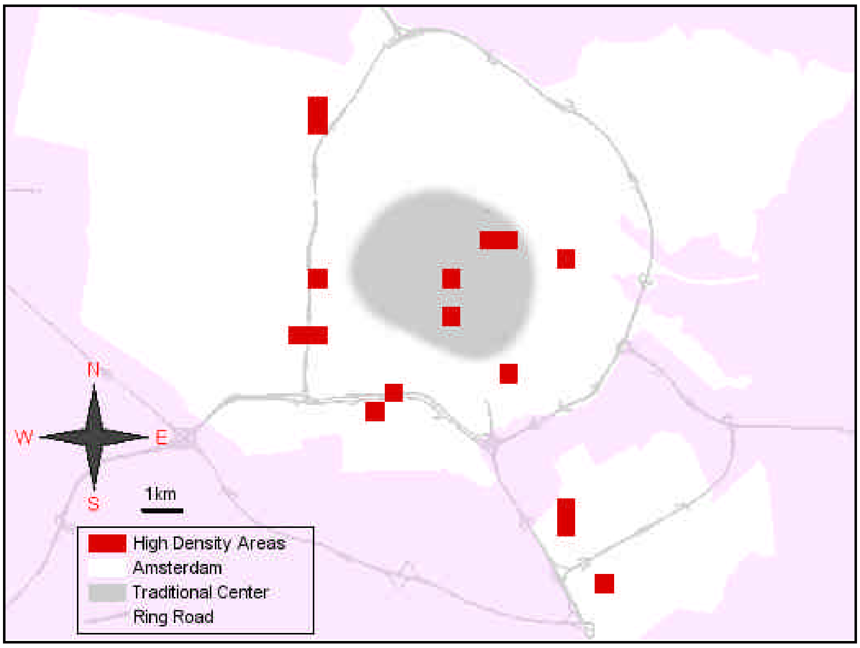


Figure 4.7. Intensity-pattern map showing high density zones (i.e. values > 3 standard deviations) in the city of Amsterdam in 2000.

Change – Vector Analysis

Another method of examining the change in volume in Amsterdam is to observe the movement of the theoretical position of the 'weighted mean centre' of the city – it may also be described as the gravitational centre[2]. This statistic is calculated using the derived building volumes as the weights and shows the effect that the newly developed zones have on the overall influences of the city. The dots on the map (Figure 4.8) represent the weighted mean centre of the urban density layer created for each time period. They represent where the spatial centre (2D average) of physical structures can be found. Most importantly this allows for some comparison as to when and where the spread of intensity was moving to and from during the past 100 years. The blue arrows (I, II, III) show the three major observable shifts in the centre of gravity. The first major movement signified by arrow I, shows the slow move of the city 'centre' in a SSW direction during the first half of the century – a clue to this slow movement is the counter balance of the development of the Amsterdam-North area. This change is gradual and shows the influence of the plans for development in the south and west. The second movement is more significant (arrow II) and is representative of the plans for the areas of Osdorp, Slotermeer, etc. to the west in the 1950's. It is a change of high magnitude which shows that the density of these new areas was relatively high. The third and most recent shift (arrow III) indicates the movement of the city in a south and easterly direction. This is evidence of the development in the Rivierenbuurt (South) and Bijlmermeer in the 1970's and 80's.

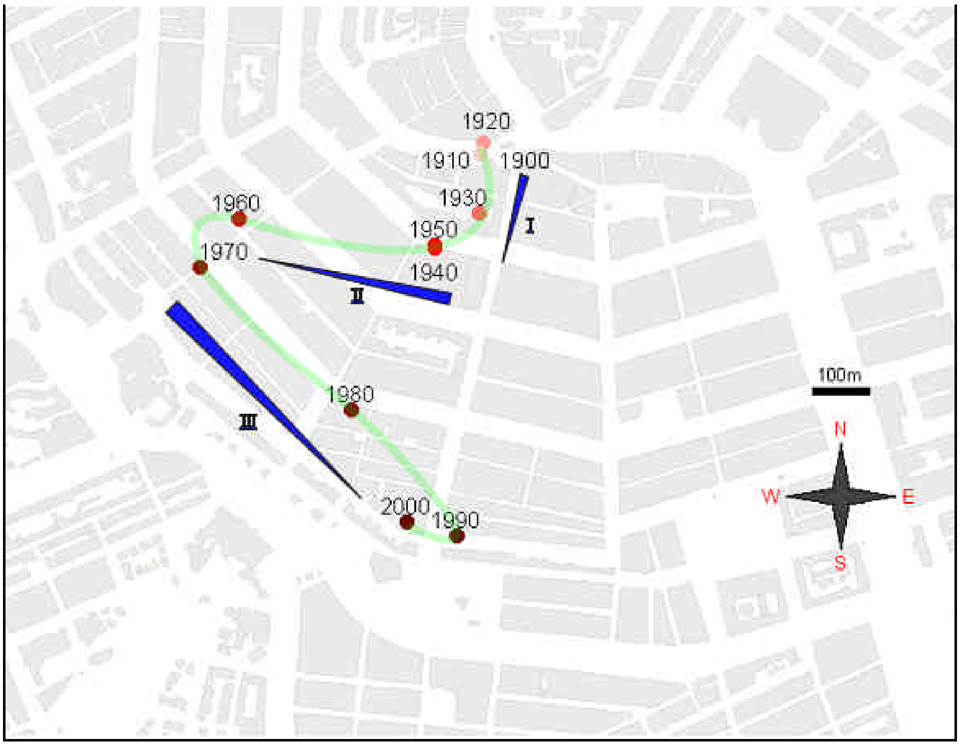


Figure 4.8. Red points showing the position of the weighted mean centre of volume in Amsterdam for each decade – the blue arrows (I, II, III) indicate the major change periods.

It is also observed that the overall change is roughly 1km to the SSW. This, again, shows the reluctance of policy makers to favour the northern part of the city (due to its accessibility isolation by the IJ River) and the prosperity of the developments in the South, South East and also in the West (as a counter to the eastward movement). Also the pull of the International Airport at Schipol cannot be ignored as an influencing factor.

Figure 4.9 indicates the difference between the weighted and non-weighted mean centres of the city. This image shows the effect that the *density* of the development-zones has on the gravitational centre of the city. The significance of this calculation is to highlight the important role that intensity plays in the study of a city and that it, ultimately, should not be ignored.

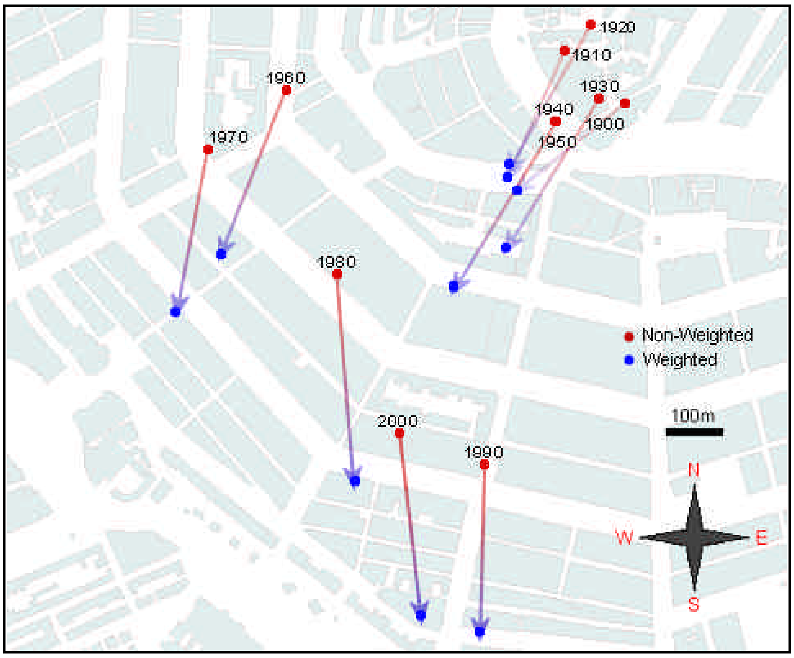


Figure 4.9. Arrows indicating the difference between weighted and non-weighted mean centres.

Change – in three dimensions

The third and final manner of drawing information from these data sets is to visualise change in three dimensions. There exist two possible manners of visualising the results. The one shown here in Figure 4.10 represents volumes per building for Amsterdam in 1970. In this case, volume values are assigned to the building polygons as the 'z-value', and as a result the model entices the observer to conceptualise density in the city – this allows the user to perceive an abstract indicator (volume) through a figurative medium (building heights). Essentially this method uses volume as a proxy for height in an attempt to model density. The second, more conventional option, is to simply display the buildings as a representation of their height – this however adds no extra significance to the meaning of density. It is effectively a simple 3D model of the city in realistic terms. On the accompanying CD (*MSc CD:* "TimeAnimation"), the animation program allows the user to view the cities morphology changing through time from this 3D perspective. The effect is a highly intuitive visual analysis into the development of the city in terms of its density over the past 100 years.

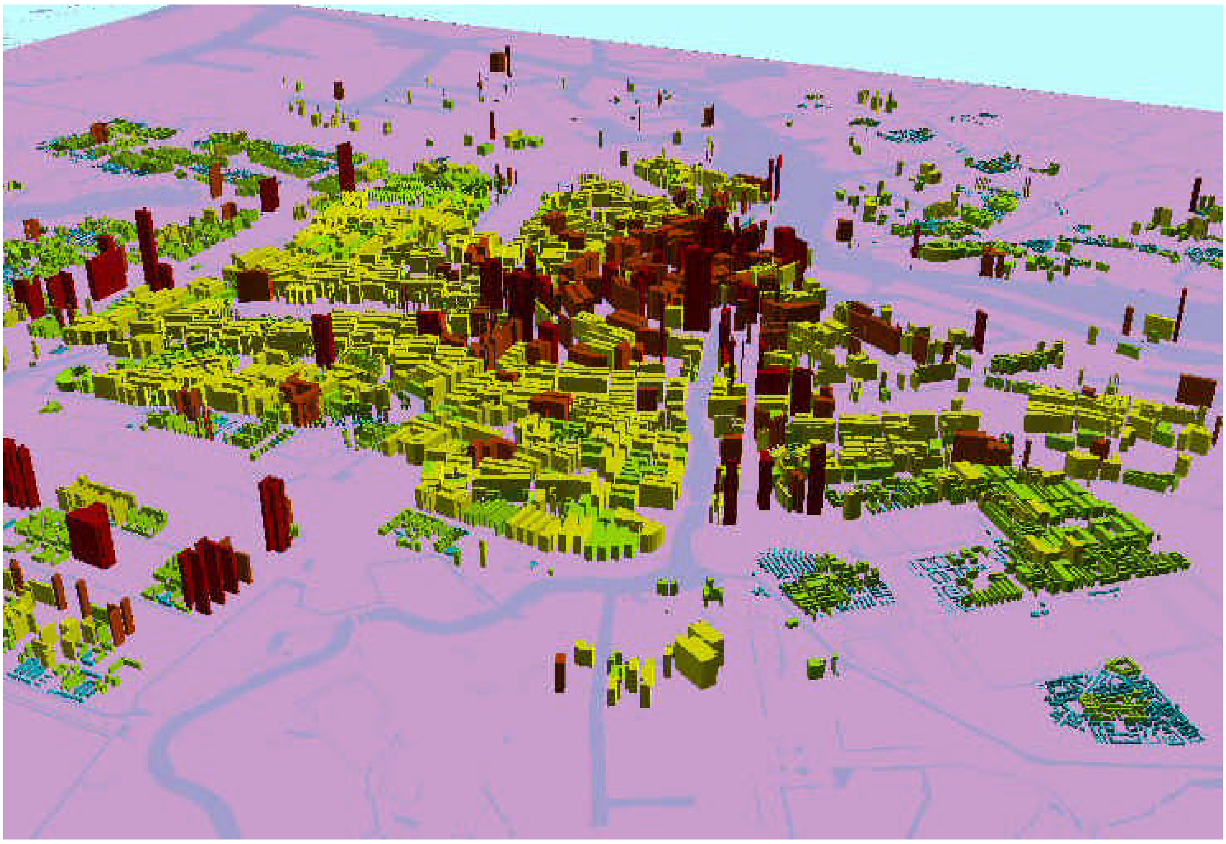


Figure 4.10. 3D visualisation model of volume in the Amsterdam urban area in 1970. *Scale changes in this view.*

4.5. Discussion

According to the hypothesis proposed at the beginning of this chapter, the results were expected to show a growing city that exhibits some evidence of being poly-nuclear in pattern, with the elements of an edge-city. From the studies outcomes, it can be concluded that the city begins to show elements of polynuclearity from 1970 onwards. In Figure 4.7, the presence of high intensity areas around the periphery of the city in some clusters (East, South and South-East) can be seen by the red colour. The central area of the city continually grows and retains its focus as the principal zone of intensity. Reflected in the weighted mean centres (Figure 4.8) is the effect that these peripheral developments have of the average 'pull' of intensity within the urban environment. The general trend moves from the centre towards the south – with the influence of the east in the 60's and 70's is countered by the latter developments in the south and extreme south east in the 80's and 90's.

In summary, the goal of using this case study to test the application of the developed urban volume methodology is successfully completed. The volume layer provides numerous possibilities to discover the spatial characteristics of Amsterdam and their change through the 20th century. These include quantitative (total volume) and visual analyses (2D, 3D maps) such as those applied here, but also others that are beyond the scope of this thesis.

Notes

1. The accompanying cd-rom contains a file named "TimeAnimation.html". This file should be opened in Internet Explorer. The functions of the program are simple and self-explanatory.

2. A gravitational centre is a calculated coordinate pair derived from the average x and average y coordinates of the input points. A weighted centre is similar, but takes a coefficient (building volumes) for each coordinate entered into the equation.

Non-weighted: $\dfrac{\sum x}{n_x} ; \dfrac{\sum y}{n_y}$ Weighted: $\dfrac{w.\sum x}{n_x} ; \dfrac{w.\sum y}{n_y}$

with w = weight;
x = *x* coordinate;
y = *y* coordinate;
n = # of points.

Chapter 5

Densities over Space: *Comparison in The Randstad*

The aim of this second case study is to investigate and compare the spatial characteristics of the four major cities of Randstad region, located in the western Netherlands, as an application of the urban volume methodology proposed in this thesis. The investigation attempts to quantify and discuss the differences in spatial pattern and total physical volumes between the urban areas; and relate the findings to reasons of urban function and historical design. Some discussion into these functions and spatial patterns is offered first; and is followed by the implementation and evaluation of the urban density methodology.

5.1. Background

The Randstad region of the western Netherlands is the most densely populated area in the country – with an average population above 1000 persons per square kilometre. The region has been influenced by a variety of strategies and policies regarding urban planning and development, in order to deal with the rising number of inhabitants (van der Cammen, 1988). Figure 5.1 below, shows the location of the study area and its four principle urban areas of Amsterdam, Rotterdam, Utrecht and The Hague (underlined in the image). As a whole, the Randstad is described as an extended poly-nuclear metropolis, in terms of form and function that is connected by a highly advanced infrastructure network (van der Cammen, 1988).

Figure 5.1. Location of the Randstad region of the Netherlands. *Adapted from: Atlas van Nederland, 2001*.

Individually, the four major urban areas have differing characteristics in terms of their spatial nature and functional dynamics; as well as in their history. After destructive bombing campaigns in the World War II, the city of Rotterdam has been rebuilt in the second half of the twentieth century into a commercial and industrial centre. Much of its allure is focused on the largest transhipment harbour in the world and all its related services and industries – as well as a well-developed trade and finance sector (van der Cammen, 1988). With a population in 2000 of just less than 600 000 and a surface area of over 20 000 ha, the city is the largest and second most populous in the study. Its size is, however, mostly attributed to the huge harbour (industrial services) area. The population density however, hints at the residential scarcity of this large urban area – see Table 5.1 (CBS, 2004).

The city of Amsterdam is characterised by its architecture, culture and tourism – it is also the national capital. Its development from a 17th century world-harbour town into a 21st century service city is currently occurring - exploitation of the airport at Schipol is central in this endeavour. Many plans exist for the development of high rise zones near this transport hub. The city is focused on the quaternary service sector – the headquarters of major banks and IT companies are found there along with the stock market and other major institutions (van der Cammen, 1988). Its houses just over 700 000 residents and is thus the most populous city in the study (CBS, 2004). The city is personified by the medium height buildings in the tourist centre and some new high rise zones around the peripheral ring road, along with the old harbour dock areas and other transport nodes.

The Hague is unique within this study – it is a bureaucratic city based around the seat of government; most of the major ministries as well as the royal residence. It is a relatively compact city, with a high population density of 6500 persons per square kilometre (CBS, 2004). This density alludes to its compact nature and modern design – and its description as a 'white-collar' city. The city of Utrecht is defined by its function as a transport hub and the central point of The Netherlands. It is also the most ancient city of the study – it has been settled from earlier than 1000AD, well before the other more-western cities in the study. This tradition defines a city with strong links with past – old buildings and remnants of the old planning directives. It has small spatial dimensions and it has the lowest population of the cities in this study. This city has fewer than 250 000 residents at a medium density (CBS, 2004).

City	Municipal Surface Area - *km^2*	Population	Population density – *pop/km^2*
Amsterdam	165.0	731 288	4 429
Rotterdam	206.5	592 673	2 841
The Hague	67.6	441 094	6 494
Utrecht	95.7	233 667	3 804

Table 5.1. Statistics for the four major cities of the Randstad region, for the year 2000. *Source: CBS, 2004.*

5.2. Hypothesis

The differences in the four cities of the Randstad, in terms of their size and function, are expected to be revealed in the results created through the implementation of the urban volume methodology. The spatial organisation of the cities is compared; and from that, conclusions are drawn as to which cities are denser, larger in surface area and which show signs of which spatial patterns. From the results obtained in the Amsterdam case study (Chapter 4), it is known that this city shows evidence of being poly-nuclear – the patterns inherent in the other cities are discovered here. According to the textual description of the cities offered in the introduction to this section, it can be inferred that certain cities should display certain density characteristics.

- Rotterdam: represents a large surface area, with relatively low overall density. The city, as a harbour town, should show low-medium density for large areas within the city, with the influence of the new city centre coming to the fore.
- The Hague: is a small city, with high density. Due to the bureaucratic nature of the city, it is expected that the majority of the high density be found near the CBD.
- Utrecht: a small city in terms of space and population. These results should show the reluctance of small populations to move away from the CBD. As such, few high densities are expected only in and around this area.

Results are presented in numerical, statistical and graphical form; as well as in intensity-pattern and density maps. The use of statistical analysis provides a common base for comparison between cities of different sizes, shapes and characteristics by using a density indicator. This density indicator is a calculation of total volumes and surface areas of the urban areas and is useful for cross-comparison of the cities. Density maps are used in a primarily observational manner and assist the viewer in discovering the overall layout of building densities – but also highlight gradients and focal areas of development. The intensity-pattern maps offer a two-dimensional comparison platform for discovering the spatial characteristics of the cities in question – these quantifications are then ready for cross-examination.

The aim of this case study is exploratory in nature; the major goal is to provide a basis for common methods for comparing cities that show different characteristics.

5.3. Implementation

The implementation process of the urban volume methodology is again followed from that described in Chapter 3 (see Figure 3.1) and is completed in a similar fashion to the case study in Chapter 4. Some small amendments are made in certain cases. Most importantly is the issue of consistency in the acquired height data set (AHN) – each urban region has different data characteristics. In the case of Utrecht and The Hague, all tall buildings are included (no limit) but values are limited to 80m in the case of Rotterdam. Amsterdam only has values below 40m, and as a result the outstanding buildings in these two cities had to be manually encoded using the skyscrapers.com web database using the method as described in Chapter 4. The encoding procedure amounts to approximately 200 buildings in Amsterdam and 30 in Rotterdam.

Once the urban volume layer has been created for each city, further analysis techniques are applied in order to better interpret the data created – to do this two separate methods are employed. Firstly, density maps are created to describe the overall distribution of density in the cities. This is accomplished by using an aggregate function[1] to expand the grid size to 50 meters based on the average cell values – this procedure creates a smoothed surface which is simpler to visualise. Secondly, intensity-pattern maps are developed by aggregating the original data layer to a 500m grid cell resolution using a maximum filter – this has the effect of selecting and highlighting the areas of high values.

The images depicting the 'traditional centres' of the city are created by using the area covered by the city at a previous time, e.g. 1900. This is a rough estimation and is meant only as a guide for the location of the CBD.

5.4. Results

Total Volume

In order to compare the relative densities of the four cities considered in this case study, an indicator has been used that is derived from the urban volume layer. The 'total volume' value is calculated by finding the product of the pixel frequency and volume per grid cell in each city (i.e. frequency *x* volume). The total area covered described as 'built-up' (i.e. bounding areas of built-up land use) located *within the municipal boundary* is then used as a divisor to find the 'average physical volume' of each urban area. This value provides a measure that is universally comparable across all the derived data sets and represents the level of densification. The definitions of the values presented in Table 5.2 are described in the figures below (Figure 5.2 & 5.3).

Figure 5.2. Red areas in the image show the buildings (volume values) and blue areas the total 'built-up' areas used in the calculation of the total/average volume indicator values. Building volumes are added only when they exist within a 'built-up' area AND the municipal boundary.

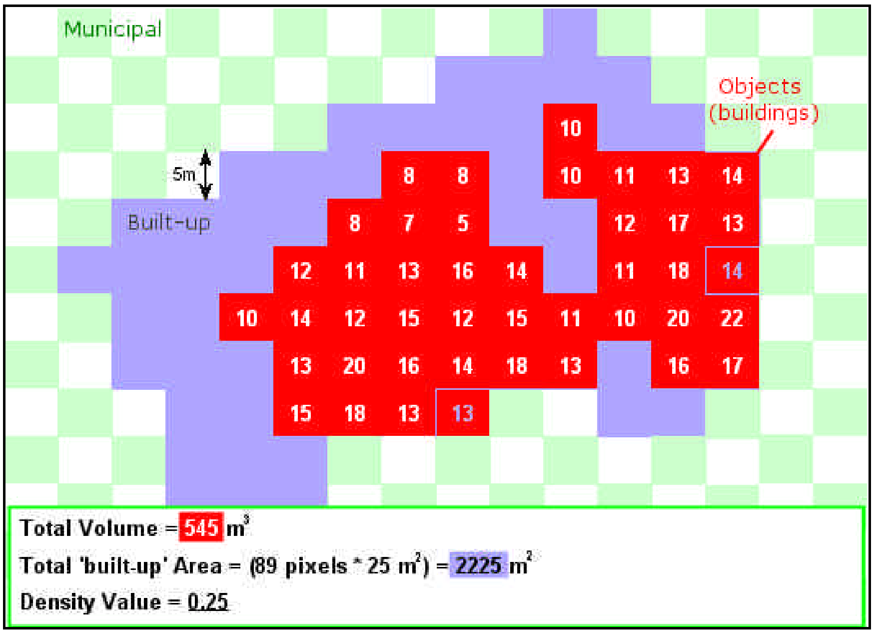


Figure 5.3. Exaggerated description of how the total and average volume indicator values are calculated.

The blue values in the table below (Table 5.2.) show this average volume value – the proxy indicator of density. The red values depict the sum of per-pixel volume values in each city – here it is observable that Rotterdam has the highest total volume (more high buildings and more surface area), with Amsterdam as second – these two cities stand out as centres that contain many high intensity land use zones. The Hague is third most voluminous city and Utrecht is last of the four. The Hague has the highest average volume which is an indication of the city's characteristic of being small in surface area, but tall in terms of structures – i.e. the densest city. Similarly the city of Utrecht shows high values for this reason.

City	Total Volume m^3	Total 'built-up' Area m^2	'Density' Indicator Value
Amsterdam	***216366027***	***10168.91***	**21277.22**
The Hague	***162122689***	***5348.70***	**30310.66**
Rotterdam	***299292333***	***15709.02***	**19052.26**
Utrecht	***92108550***	***3622.36***	**25427.76**

Table 5.2. Table showing the volume, area and density indicator value for each of the four cities.

Graphical analysis

The graph below (Figure 5.4) describes the frequency of building heights in the four investigated cities. The y-axis (logarithmic scale) describes the number pixels present for each height value on the x-axis. From these data it is obvious to note the decline in frequency as the building height increases. The points shown on the graph allude to the characteristics of the cities in question. The dominant position of the orange squares (Rotterdam) at both low and high values shows its size and large total number of buildings. The blue squares of Amsterdam are very similar, but are slightly more dispersed – this shows how the city is similar in type to Rotterdam, but on a somewhat lesser scale. Utrecht (green) shows the lowest values in both height and frequency – further strengthening the view that it is the smallest and 'shortest' city of the group. Both Utrecht and The Hague have very little evidence of high buildings (above 80m), although The Hague has a wealth of structures just less than 80m. These data are created for the year 2000, but since then some major changes have occurred in the high-building arena, especially in The Hague, which unfortunately do not show in the analysis here.

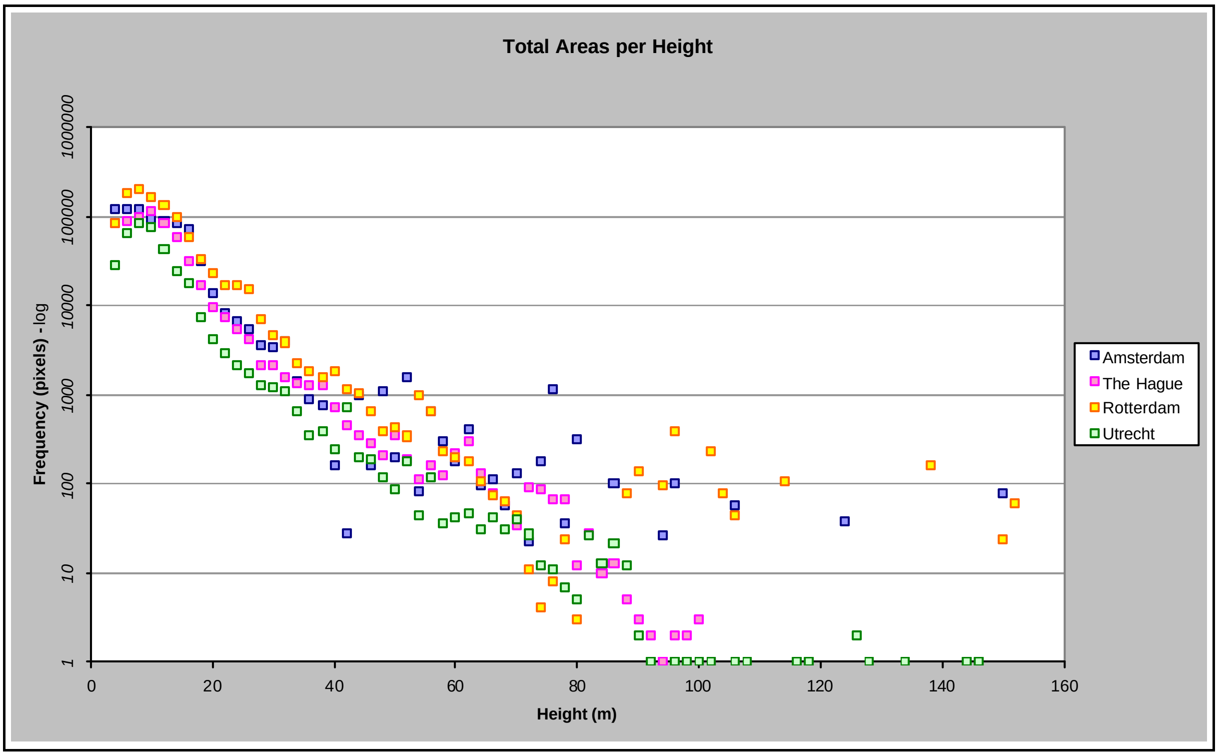


Figure 5.4. The graph shows the distribution of building heights per pixel area for each city, as well as a trend curve representing these point clouds (a measure of total volume).

Density maps

One particular method of evaluating density in the urban areas is to create density maps – they have been created for Utrecht, Rotterdam and The Hague (Figure 5.5); see Chapter 4 for an in-depth discussion of Amsterdam. These maps allow for observations as to where the areas of high/low densities occur and assist in determining the patterns present in the areas. In each case, the values represent categories of standard deviations from the mean – these statistical values are calculated independently for each city and they are shown on the map itself. The results are maps that show the relative intensity in each urban area. This approach allows one to compare the 'internal level of densification' between the cities. Red colours depict high density zones and in all three cases are most dominant in the traditional centre of the city – there are development zones noticeable in the North-West of The Hague (Scheveningen) and Utrecht North. Rotterdam shows no definitive evidence of outlying high density zones and its pattern is distinctly central, despite the oblong shape of the municipal boundary where there are some dispersed areas of medium/high intensity – all along the river (and harbour) towards the West of the centre. Also noticeable in The Hague is the medium/low development 'strip' between the traditional centre and the coastal zone in the North-West; whereas Utrecht shows signs of a circular development pattern around the CBD, with only an emergence in the North around the ring road.

In each of these cases the pattern of development seems to be guided by some pulling and pushing factors. The Hague shows observable evidence of development between the CBD and the coastline – the high intensity zone at the coast is made up primarily of residential high rise apartment buildings that serve mainly the needs of the tourism economy. This coastal zone attracts density from the CBD toward it. Most of the high density zones in Rotterdam are situated in and directly around the CBD – there are some medium intensity areas along the river (harbour area) towards the West. This is evidence of the major function of the city as a commercial centre (CBD) and an industrial powerhouse (harbour). Utrecht shows very little deviation to a centrally pivotal city pattern, with only the circular ring road as an enticing factor to new development plans. This highlights the lack of external pulling factors for the city. Medium-intensity developments are to be found along the transport infrastructure in a network pattern – agreeing with the definition of the city as a transport hub.

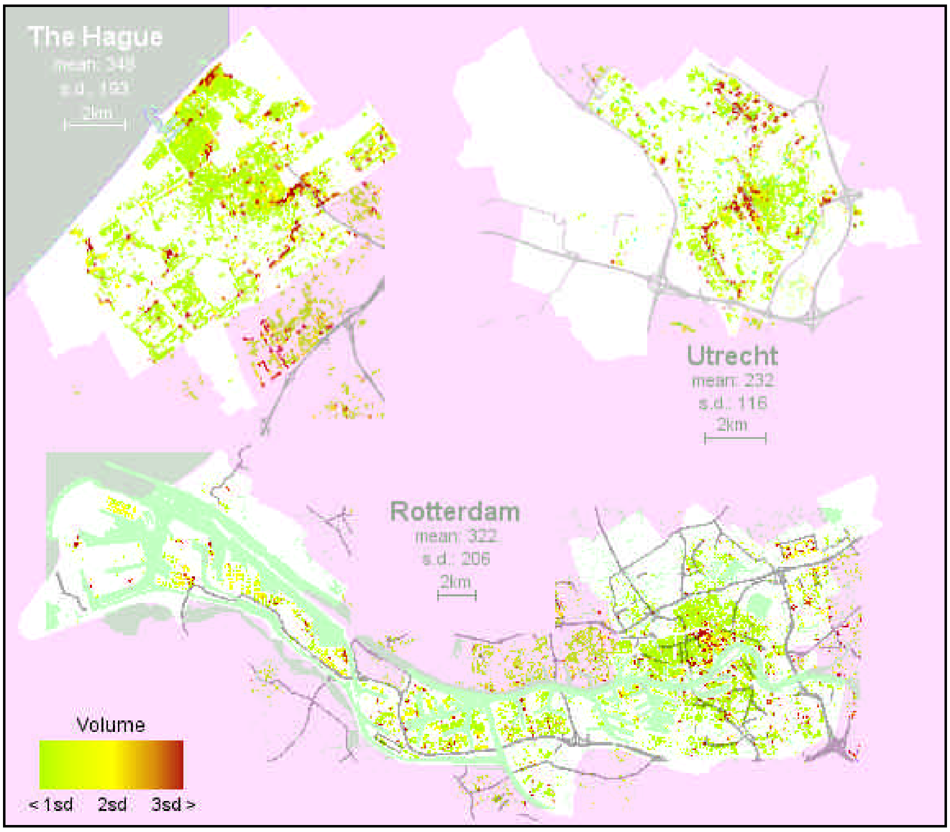


Figure 5.5. These density maps show the range of volume within each independent city. Values range from the mean to greater than three standard deviations (sd), which define areas of high and medium density.

Intensity-pattern analysis

Further analysis of the derived data reveals the spatial patterns of each urban area, based on the dispersion of high intensity land use zones. This is achieved by initially aggregating the urban volume data, using a maximum filter, to a 500 x 500 meter grid cell resolution – these values are then reclassified to show only values greater than three standard deviations and thus reveal only the extremely high values in the data set. The results of this analysis are shown in Figure 5.6 below – the red dots represent these areas of high relative intensity. The calculations are made independently for each area and thus represent areas of relative intensity within the city itself. Immediately obvious from these images is the division between the two larger cities of Amsterdam and Rotterdam and the smaller ones of Utrecht and The Hague. They show significantly more areas of high density, however those found in Rotterdam are concentrated in, and directly around, the traditional centre. The other three cities show signs of the formation of new high density zones outside the CBD, with Amsterdam being the most pronounced. Utrecht has three 'new centres' all developed along the ring road; and The Hague has just one in the North-West – the conglomeration of land use intensity in the centre is a result of the primary function of the city as the seat of government. In general, it can be deduced from the images that Amsterdam is the city with the most high density zones – as well as the most dispersed pattern of these.

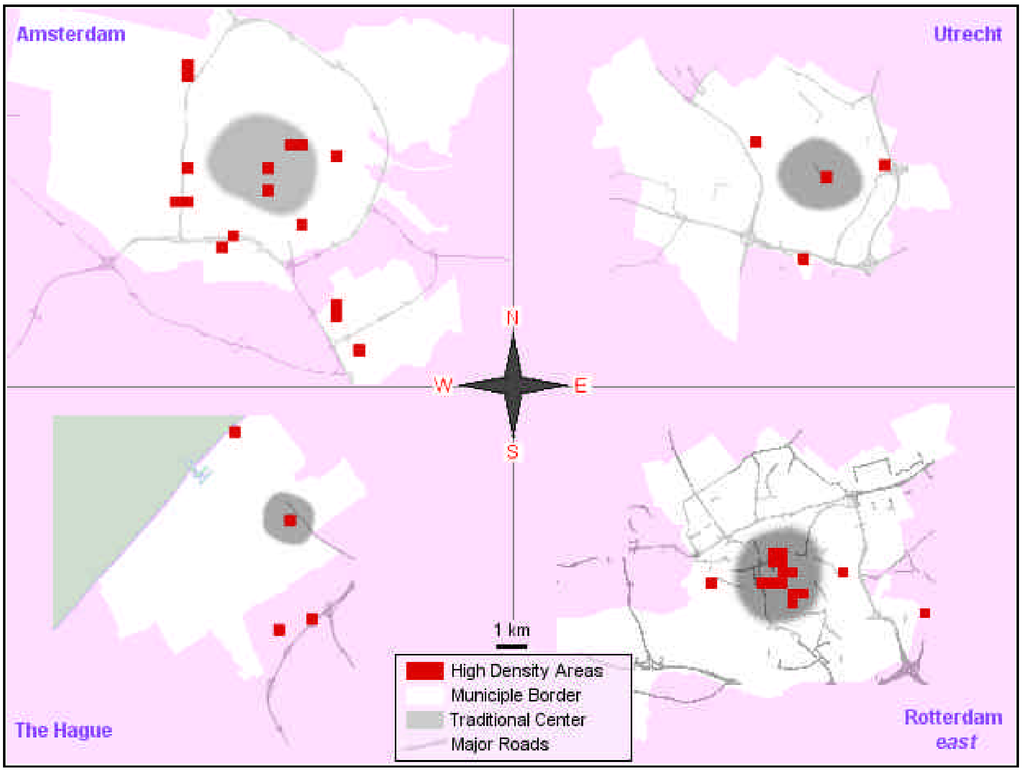


Figure 5.6. Intensity-pattern maps for each of the major cities in the Randstad. Red dots represent areas (500m x 500m) of high physical density.

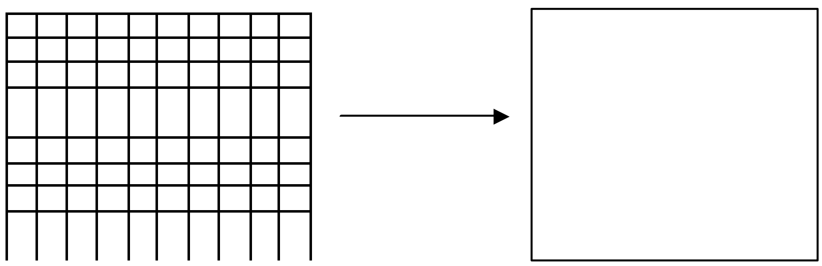
5.5. Discussion

The investigation of densities in the four major cities of the Randstad region has proven successful. By using the derived volume layers – created by following the methodology presented in Chapter 3 – rich data were created. Some analyses were completed and discussed that show some interesting results. It is plain to see from these, the differences that exist in the cities in terms of their spatial form. This was proposed in the hypothesis, which states the differing roles that each of these cities fulfils. High volume cities found at Amsterdam and Rotterdam, with high density in The Hague.

The Randstad investigation shows positive signs for the implementation of the urban volume methodology in such an application. The data it produces can be analysed to gain further insight into the spatial characteristics of the cities in question. The ability to produce multiple data sets that are independent from each other, but still comparable is invaluable in the aim of discovering the differences in heterogeneous cities.

NOTES

1. An aggregate function may also be known as an ‘expand function’, depending on the software used. The function simply decreases the cell resolution by creating one cell for every (in this case) 10 blocks in each direction, and assigns it the average value of those 100 previous cells.



Chapter 6

Evaluation and review

6.1. Summary

The continual need for more commercial and residential space has resulted in an ever increasing level of density in major urban areas in Western Europe and other parts of the world. The influence of such high-intensity land use zones on the urban morphology is similarly escalating and the need to incorporate the vertical aspect of cities in academic studies is evident. This thesis offers a complementary method to traditional urban studies by determining urban volume and providing an indicator-method for quantifying urban density.

The present study introduces a method to describe urban density. This is completed through a sequence of steps. Firstly, a review into urban geography and urban studies is provided as a backdrop to the field of study. A discussion on the current state of research, future possibilities and specific focus on urban study in The Netherlands reveals the innate need for fully incorporative methods that include the effect of the third dimension. The second step is the theoretical and practical development of a methodology for creating the urban volume layer. The design of the process revolves around the amalgamation of high detail data sets – including height data, building data and dates – through a series of GIS operations to develop a layer that describes the volume per pixel of all cells classified as ‘buildings’ within a chosen urban study area. The third and final step in the thesis is the practical implementation of the methodology in two case studies in which the time and space component of urban density are investigated. These components are assessed by applying the methodology in the Randstad region of the Western Netherlands. The time component is studied in the city of Amsterdam for the period from 1900 to 2000. The urban volume layer is created for each decade of that century and analysis is carried out to discover where and when the major changes in urban development occurred. The results are correlated to the development history of the city. The space component covers the four major cities of the Randstad region. Urban volume layers are created for each defined city area and the resulting data are then compared by the use of indicators, map analyses and visual interpretation. Both of these case studies produce outcomes that are interpreted by means prescribed by the background knowledge of urban studies.

6.2. Evaluation

The original goals and aims of this research are outlined in the opening chapter. It is prudent now, at the completion of the study, to offer some response to the initial research questions. The first main question is: can some improvement in traditional urban study methods be realised by the development of an urban volume methodology? It is clear, from the definition and tests performed on the presented methodology, that this is indeed possible. A process has been developed and streamlined to make the most effective use of newly available high detail data to develop a grid data layer that describes densities at a resolution of 5 meters. Despite the inherent data problems discussed in detail throughout this thesis, the resultant volume data are accurate and useful. The high resolution of the data allows for further in-depth data discovery, through the use of standard raster analysis such as filtering and aggregation. This new method is more useful than traditional studies in this regard – no other method uses data that is as finely detailed at such high resolution.

The second main research question posed is whether the new methodology may be useful in investigating the urban environment. This question is answered through the development of, and response to, three sub questions. To begin with, one can first ask whether the cities studied are focused on development in the centre or around the periphery of the city – essentially to quantify the urban pattern present. This question was answered in the Amsterdam case study through the creation of time series density data. It is noticeable that the city, in the recent past, exhibits evidence of major developments around the 'ring-road' and other major network connections. These data show the slow changes in the centre of the city and significant and rapid changes in certain outlying areas. There is strong evidence from this data that the city is not focused on 'densifying' the old-centre. Instead the city is geared to aligning with the regional plans for densification in certain areas around the major transport infrastructure, to create a more commercially prosperous and functional urban area.

The second sub-question is whether the morphology of the city can be fully described by using the volume methodology. Both case studies demonstrate the capabilities of the methodology in this regard. Results are offered in numerical (indicator) values, histograms, statistical analyses, two-dimensional density maps and pattern maps, as well as in three-dimensional visualisation models. This array of rich data assists an expert observer in deciphering the overall shapes, patterns and changes in the urban morphology. Evidence shows the significance of using volume as a weight in these studies, by comparing it to a non-weighted variant. Many analytical avenues are explored using these data in the two case studies. All four dimensions of density are presented by the location, the vertical magnitude and the change over time. However in-depth these outcomes may be, the methodology still has areas for improvement and as such, cannot claim to be a *comprehensive* tool for urban density study and should be used along with some other methods for better results.

The third sub-question asks how densities can change over time and how densities in different cities can be compared to each other. The Amsterdam case study shows the gradual changes in the city over 100 years, making use of animations and 3D models to describe where, and by how much, densities have changed. It is evident in the case of Amsterdam that much of the spatial dynamics are prescribed by the thorough adherence of the authorities to spatial planning – the effect of densification directives, deconcentration directives and war can be seen in the changes in density of the city over time. The Randstad case study shows some methods for comparing densities in cities that are fundamentally different in terms of the size, function and location. The use of the 'volume indicator' or 'total volume' value shows the differences in makeup of the four cities. High density is evident in Utrecht and The Hague, while larger volumes occur in the larger cities of Rotterdam and Amsterdam. These density differences correspond to the differing functional status of each city: low density in industrial cities and high density in bureaucratic and ancient cities.

A secondary aim of the thesis was to test the applicability of GIS to carry out the required tasks. Some discussion into the software and functions used is offered throughout the thesis. This alludes to the complexity involved in the choice of approach. However, the final product shows that the capability of certain software packages to accomplish the goals. Some interoperation was required and conversion was efficient and accurate. This attests to an improving state of integration of software and file formats in the field of GIS. With this successful implementation it is safe to say that furthering its use in other related urban studies is both feasible and invaluable.

In general the development and implementation of the urban volume methodology in describing urban density in Dutch cities has proven successful. Each outlined objective has been met with a certain degree of success. Furthermore, although there are some shortcomings to the methodology in its current form it is clear that there are several feasible options to further develop and improve the methodology, in order to overcome these limitations. These options are discussed in the next section.

6.3. Recommendations

The acknowledgement of certain shortcomings in the developed methodology and in its implementation does not imply a lack in potential for further improvements. Major advances can be (and are currently being) made in the quality of the data, which is used in the methodology. The laser derived height data proved inconsistent and impractical by providing incomplete data in certain areas and removing high values in specific cases. Fortunately, future versions promise to provide more structured and consistent data, thus eliminating the need for manual encoding, which will save time and increase the overall level of accuracy. Similarly, the errors of completeness and 'the island-polygon problem' present in the building vector definition file should be minimised by the data provider, which again would result in a higher level of accuracy in the methodology. The methodology itself can be improved in three main ways. Firstly, the creation of the underlying surface model to extract actual building heights can be refined by using more appropriate and accurate data. Secondly, the selection of buildings from the height data could be based on more appropriate criteria, as opposed to the selection of values above the arbitrary height of 3 meters, which was employed in this study. The method chosen may be replaced by a more robust filtering technique that automatically defines buildings from the break-lines in the data. Thirdly, a better and more precise definition of the Area of Interest would allow for a more specific focus on urban areas – these definitions depend on the exact purpose of the application. The application of the methodology also has some other shortcomings that can be improved: for instance the use of filtering techniques may be better reinforced with some cognitive reasoning – applying visual perception techniques to better understand the patterns within the city. Since the nature of the case studies is exploratory it should also be noted that analysis by an expert urban geographer may provide more meaningful conclusions to the ones offered here.

The research presented in this thesis is unique in its method and outcomes. It focuses on strictly physical features to model the physical environment and does so at finer scales than previously possible. However, it remains based on some traditional models of urban land use study. Due to this experimental beginning it is prudent to offer some future research directions that will aid in creating a better, more consistent and more applicable methodology. As is mentioned elsewhere in this chapter, some study into the capturing and processing of laser-derived heights would be advantageous to any study that aims to use data of high accuracy in urban environments. Some future developments in the field of cognitive perception and definitions of density in urban areas will help to focus studies such as this one to more specific fields. From a technical perspective, the future improvement of functional 3D modelling environments (perhaps even virtual reality) will aid in better methods of data exploration and presentation. Further development of the methodology to extrapolate possible forecasts would be a great innovative application for urban volume which can be used by planners to 'see into the physical future'. All in all, this successfully developed model has some viable areas for improvement, and holds promise for much future research.

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Appendix A

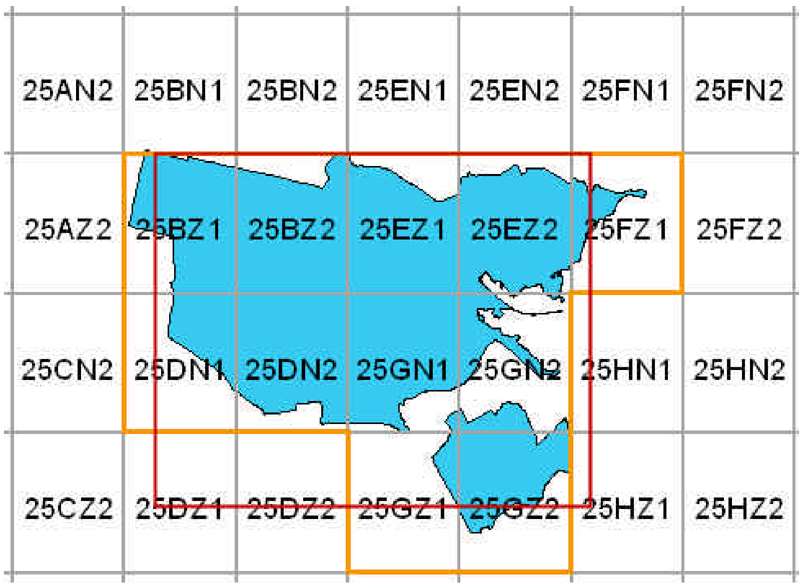
Selection of Urban Areas of Interest

A.1. Map Sheets

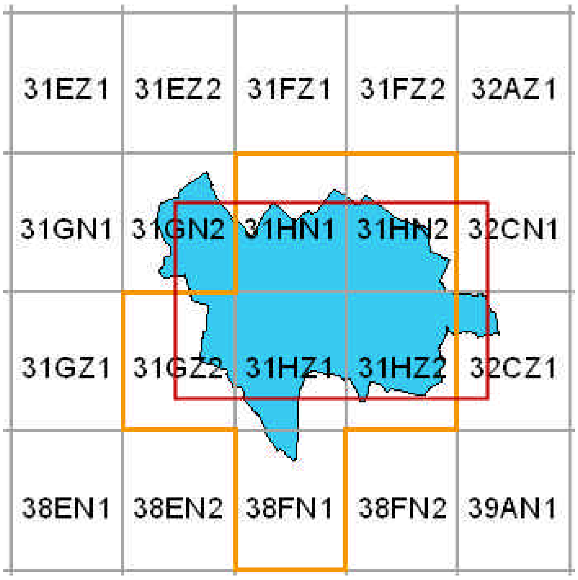
The map sheets shown here are the selections made and used throughout the thesis. Their selection is based on the top10vector/AHN sheets numbers that are covered by the municipal boundaries.

Legend

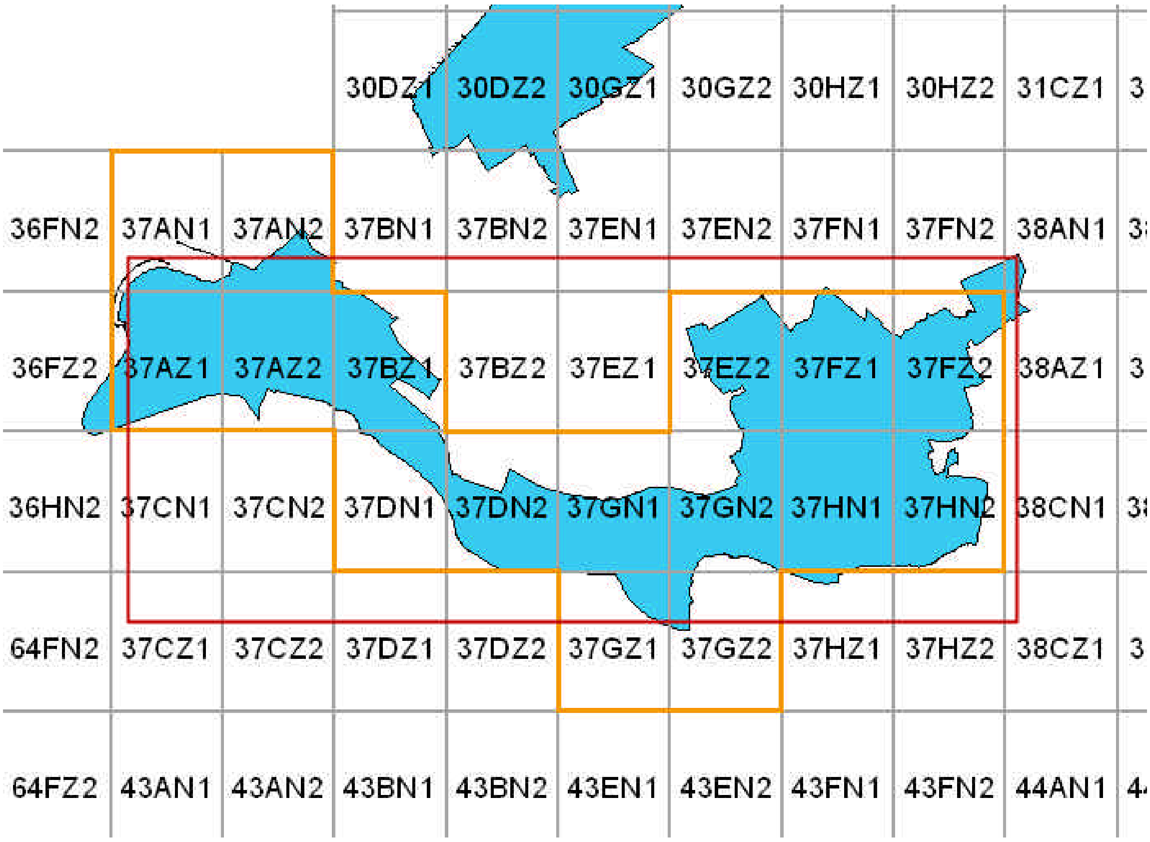
Amsterdam



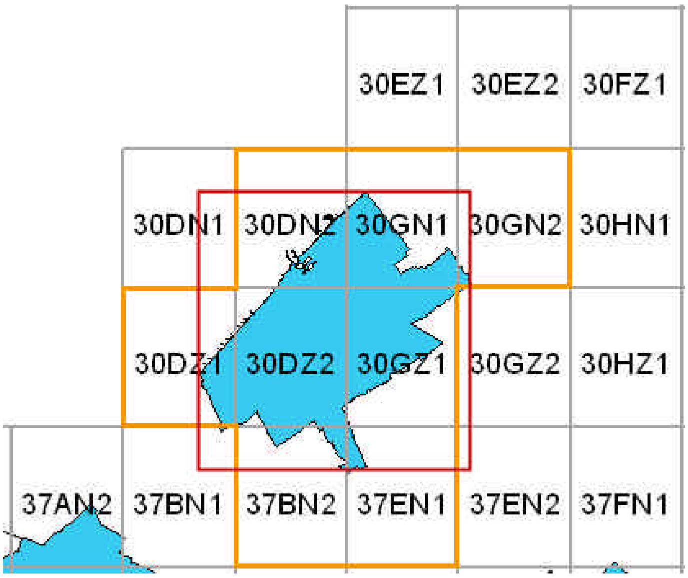
Utrecht



Rotterdam



The Hague


30EZ1
30EZ2
30FZ1
30DN1
30DN2
30GN1
30GN2
30HN1
30DZ1
30DZ2
30GZ1
30GZ2
30HZ1
37AN2
37BN1
37BN2
37EN1
37EN2
37FN1

Appendix B

Source Code

B.1. MABR

The minimum bounding rectangle script. Developed in Avenue for ArcView 3.3.

```
'**********************************************
'*                                            *
'*  Script that creates and shows a shapefile *
'*  that represents the minimum bounding rect *
'*  angle (MABR) of the built-up areas input  *
'*  shapefile.                                *
'*  Author: Richard Kaufholz                  *
'*  Date Modified: 17-05-2004                 *
'*                                            *
'**********************************************

'**********************************************
'set document variables
'must be the active document, with the built-up area shpfile at the top
'**********************************************

theDoc = av.GetActiveDoc
thePolyTheme = theDoc.GetThemes.Get(0)

thePolyFTab = thePolyTheme.GetFTab

'**********************************************
'create a field to dissolve polygons
'**********************************************

thePolyFTab.SetEditable(true)

concat = Field.Make("concat", #FIELD_DECIMAL, 2, 0)

thePolyFTab.AddFields({concat})

for each i in thePolyFTab
  thePolyFTab.SetValue(concat, i, 1)
end

'**********************************************
'summarize the shapefile based on the new concatenation field
'**********************************************

if (thePolyFTab.IsEditable = true) then

  area_field = thePolyFTab.FindField("Area")

  theNewFTab = thePolyFTab.Summarize( "merger".AsFileName, Shape, concat,
```

```
  {thePolyFTab.FindField("Shape")}, {#VTAB_SUMMARY_SUM})

  theNewFTab.CreateIndex( theNewFTab.FindField( "Shape" ))

  thePolyFTab.SetEditable(false)

end

'***********************************************
' find the minimum bounding rectangle (MABR)
' convert it to a polygon
' enter it into a new shapefile
'***********************************************

theRect = theNewFTab.ReturnValue(theNewFTab.FindField("shape"), 0).ReturnExtent

theRectPoly = theRect.AsPolygon

theRectFTab = FTab.MakeNew("rect".AsFileName, Polygon)

theRectFTab.AddFields({ Field.Make("name", #FIELD_CHAR, 10, 0) })

recNum = theRectFTab.AddRecord

theRectFTab.SetValue(theRectFTab.FindField("shape"), recNum, theRectPoly)

'***********************************************
' add the two new shapefiles to the view
'***********************************************

theDoc.AddTheme( FTheme.Make(theRectFTab) )
theDoc.AddTheme( FTheme.Make(theNewFTab) )
```

B.2. Mosaic Grids

A script created to concatenate grid themes in ArcView 3.3. Code is written in Avenue and takes the orginal AHN grids as arguments.

```
'**************************************************
'*                                                *
'*  Script to mosaic (join) the individual AHN    *
'*  grids.                                        *
'*  Author: Richard Kaufholz                      *
'*  Date Modified: 29-06-2004                     *
'*                                                *
'**************************************************


'**************************************************
'set the document variables
' must be the active document. only the grid themes
' present
'**************************************************
```

```
theDoc = av.GetActiveDoc

theGThemeList = theDoc.GetThemes

theGridList = {}

' ***************************************************
' loop through the grid themes - ass each grid to a
' list
' ***************************************************

for each i in theGThemeList
  theGridList.Add(theGThemeList.Get( theGThemeList.Find(i) ).GetGrid)
end

' ***************************************************
' mosaic grids in the list
' add new theme to the view
' ***************************************************

theNewGrid = theGridList.Get(0).Mosaic(theGridList)

theGridTheme = GTheme.Make(theNewGrid)

theDoc.AddTheme(theGridTheme)
```