Fractal Geometry, Complexity, and the Nature of Urban Morphological Evolution:

Developing a fractal analysis tool to assess urban morphological change at neighbourhood level

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Abstract

During the last three decades, an increasing amount of evidence suggests that the new theories of complexity and fractals are building up realistic views to study complex nature of urban forms and functions from micro to macro scales. Such works are based mainly on the concept that cities are evolving and changing from the "bottom up" according to their local rules and conditions at micro city scales by which more morphological and functional orders emerge at macro city scales. From a morphological point of view, it can be interpreted that urban forms and patterns emerge at macro scales of a city based on the sequence of changes occurring in micro scale urban units (buildings) within it. While complexity theorists are questioning the deterministic top down approach in current urban planning and design, the problem is that there are still gaps in formulating how the complexity theory may be applied in practice, particularly where it relates to city shapes, forms and patterns. This research addresses the lack of feasible tools for measuring changes in the physical complexity of urban morphological features and focuses on change analysis in urban patterns at local and neighbourhood scales.

The research, therefore, has sought to develop a fractal analysis tool to measure the complexity of urban patterns by calculating fractal dimensions of them. It proposes Fractal Neighbourhood Identification codes (FNID) as a kind of digital signature of a city structure, which reveal the level of physical complexity that urban patterns demonstrate at neighbourhood and local scales. Furthermore, the research has succeeded to produce a 'fractal map' of a city for the first time. It has employed fractal calculation software (Benoit) in linkage with GIS software (ArcMap) to convert numerical data into pictorial data and to visualise spatial fractal dimensions in terms of the fractal map. This map could then provide a basis for fractal identification and classification of urban patterns and, more importantly, the analysis of pattern changes over both space and time.

A district in the north of Tehran (Shemiran) has been selected as the case study for this research. The proposed fractal analysis tool has been found to be useful for the fractal interpretation of urban patterns, suggesting a realistic way of pattern identification and classification. Two sample cases within Shemiran, one originated from a gradual organic growth and the other from a rapid planned development, were selected to test the potentiality of the method in identifying homogeneity and heterogeneity that the patterns exhibits over different places. The same method was employed to measure the changes occurring over different periods. The aerial photos of Tajrish, the centre of Shemiran, between 1956 and 2002 were analysed to examine quantitatively the degree of changes that the urban pattern related to each neighbourhood experienced during this period. The research suggests that the same method can be applied to the entire metropolitan city of Tehran and more generally to any other cities.

The fractal assessment method suggested in this research can also be employed by urban designers, planners, and decision makers to predict mathematically the degree of changes that architectural design proposals or any other kind of urban interventions may impose to the physical complexity of an existing urban fabric, before their real implementation. In this sense, the proposed fractal assessment technique could contribute a more flexible appraisal method for urban conservationists who are keen to preserve urban characteristics while allowing innovations and recreations in the context of an historic urban district. Finally, the research also took another step forward in developing a practical tool for planners who believe that the current top down deterministic planning and design routine should be revised by flexible bottom up approaches.

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CHAPTER ONE

INTRODUCTION

1.1 Introduction and the Rationale for the Research

1.1.1 The city of organized complexities

> 'Cities happen to be problems in organised complexity, like the life sciences. They present situations in which half a dozen or several dozen quantities are all varying simultaneously and in subtly interconnected ways.... They are many but they are not helter skelter; they are interrelated into an organic whole' (Jacobs, 1961; quoted in Batty, 2005, p.1).

> 'There are several adaptive forces in society which, directly and indirectly, influence the life and shape of urban areas: there are demographic, economic, technological, and cultural forces.... They operate at all scales.... The problem in discussing each separately is that, in real life, most of these factors are complexly interlinked in a web of causes and effects' (Gottmann, 1978, quoted in Larkham, 1996b, pp.37-38).

The city and its problems are the product of considerable diversity of socio-spatial processes, elements, variable problems, and several adaptive forces associated with politics, economics, technology, culture, climate, etc. There are also many factors playing a role in each of these processes and forces, which make the modern city more complex and its problems multi-factorial. These factors 'operate at all scales in all settlements and throughout history' and they are 'complexly interlinked' (Larkham, 1996b, p.37). Therefore, it should be obvious that the reductionist approaches to the city systems, which reduce their problems to their constituent parts with one-, two-, three-, and four-factors, cannot cope with the complex nature of problems posed by the modern city (Weaver, 1948; Jacobs, 1961; Batty, 2005). In this sense, cities, like the life sciences (e.g. biology), are recognised as 'problems in organised complexity' (Jacobs, 1961, p.432).

The difficulties of addressing this type of problems by purely reductionist approaches become even more apparent when considering the following two defining features: (a) City systems, like living organisms, are characterised by a complex organization, which results from a network of interactions involving a high degree of nonlinearity (b) they are open systems; that is, their form and function are in a state of permanent flux, continuously influencing and being influenced by their wider environment, exhibiting "emergent properties" (Portugali, 2000; Walleczek, 2000). Figure 1.1 visualises the concept of a complex system with these two defining features. The whole structure is in a non-equilibrium state, emerging through the continuing interactions between micro and macro processes. In this sense, emergent properties or surprising events in a city – like a living organism – can be defined as properties that are possessed by a dynamic complex system as an organic whole, but not by its constituent parts alone (see also Chapter Three, section 3.2.2 and appendix A for definitions).

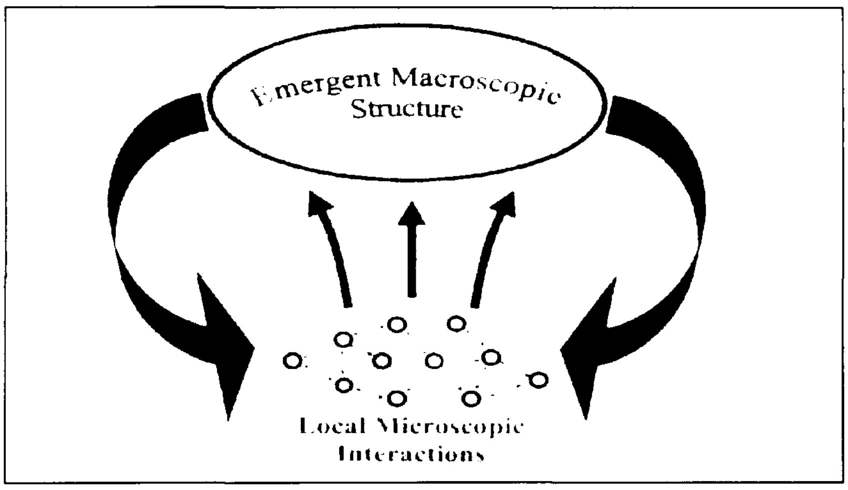

Figure 1.1: The dynamical interdependence between local (micro) interactions and the emerging global (macro) structure. (Walleczek, 2000, p.3)

However, cities have not generally been treated as complex systems. The architects, planners, urban designers, and builders of settlements treated them as simple predictable systems to be ordered and reduced to their components in order to facilitate urban modelling and to tackle city problems (Batty, 2005). In planning and design, the rise of the science of complexity has engendered a shift between the old view that sees cities as simple, ordered, structured, expressible by smooth lines and shapes towards a view that cities are complex organisms, evolving from the bottom up according to their local rules and conditions, which manifest greater order across many scales and times.

Jacobs (1961) was one of the first calling for the science of complexity in the effort to understand urban problems better and design solutions consistent with the way the city works. Alexander (1964, 1965) said much the same advocating the idea that the city should be gradually developed from the bottom up though slow adaptive processes, 'but that since the Renaissance, and certainly since the Industrial revolution, this link had been broken' (Batty, 2005, p.6). In his more recent work, Alexander (2002b, 2004) has brought forward the need for a theory that can cope with the nature of urban complexity:

> 'We are surrounded by complexity. The modern city is immensely complex.... It would be natural to expect, therefore, that we must have a theory of complexity, that we have an effective and sensible way to create complexity. Faced with the need, growing everyday, to create successful complex structures all around us, one would expect that we have at least asked ourselves how, in general, a complex structure may become well-formed' (Alexander, 2002b, p.180).

Alexander (2002b) argues that all the well-ordered complex systems we know in the world, at least those viewed as highly successful, are generated structures, not fabricated structures. According to him, this fundamental law is, to all intents and purposes, ignored in 99% of the daily "fabrication processes" of society (see figure 2.25 in Chapter Two, and table 3.1 in Chapter Three). If our buildings and cities should reflect our worldviews, we must modify them to come closer to what we know about the organic universe – 'nonlinearity, emergence, complexity, and self-organization' (Jencks, 1997, p.159). Otherwise, day by day we will build up an alienated environment with no living spatial characteristics.

1.1.2 The research background and the theoretical motivation

The motivation for this research stems from two parallel, but related, scientific events that happened over three decades ago. The first was the rise of chaotic dynamics in domains such as mathematics, cybernetics, and physics during the 1970s and 1980s (see Gleick, 1987; Prigogine and Stengers, 1984; see also Chapter Three, section 3.1). The second was the discovery of fractal geometry by Benoit Mandelbrot in the 1960s, and in his influential book, *the Fractal Geometry of Nature,* facilitating the study of many irregular and seemingly amorphous man-made and natural patterns (see Mandelbrot, 1983; see also Chapter Three, section 3.3). Both chaotic dynamics and fractal geometry have been employed in a wide range of sciences dealing with self-organised complex phenomena, including those related to urbanism (see table 4.1 in Chapter Four). In the following statements, Batty (2005, p.5) hints at the relationship between these new theories:

> 'Processes that lead to surprising events, to emergent structures not directly obvious from the elements of their process but hidden within their mechanism, new forms of geometry associated with fractal patterns, and chaotic dynamics – all are combining to provide theories that are applicable to highly complex systems such as cities.'

From the mid 1990s, these two parallel paradigms began to merge under the new theory of complexity (see also Flood *et al*, 1993; Byrne, 1998; Wilson, 2000), which in the case of urban studies led to the proposition of the theory of fractal cities by Batty and Longley (1994). While the concern of chaotic dynamics is how a city as a complex system behaves, fractal geometry provides subtle views to the study of urban morphological complexity. Both subjects play a major role in the construction of this thesis, assisting in the understanding of the nature of urban functional and morphological evolution. However, as the title of the thesis suggests, the focus of the research is on the second paradigm – fractal geometry as dealing with urban morphological complexity.

1.1.3 The fractal analysis of urban morphology and the research focus

> 'Urban morphology refers to the study of physical (or built) fabric of urban form, and the people and processes shaping it' (Larkham and Jones, 1991, p.55).

There is limited amount of 'research on the physical form of cities' (Larkham, 2006, p.118). Moreover, much of this work is on the physical urban form not the processes shaping it. 'Fifty years ago, theories of how cities were structured in spatial terms hardly existed' (Batty, 2005, p.2). The limited amount of research on physical form and urban evolution draws attention to the lack of appropriate theories, methods, and accurate tools in the hand of urban morphologists.

From the Renaissance architects (e.g. Leon Battista Alberti, 1404-1472) and their geometrical and mathematical analysis methods to the recent morphologists (e.g. Conzen, 1962, 1988) and their metrological and morphometric analysis methods, the linear principles of Euclidian geometry have been the common ground. These methods have been based on the detailed measurement of plot and building sizes with especial reference to relative proportions of width, length, and height (see Whitehand, 1981, 1987b, 2001; Slater, 1990a, 1999; Larkham 2004b, 2006; Steadman, 2008). Yet the inevitable linearity of Euclidean geometry associated with all of these methods does not allow them to explore the subtle complexity existing in urban forms and patterns (see section 2.2 in Chapter Two).

Over the last fifteen years, there have been a growing number of publications suggesting the application of fractal analysis in the study of urban morphological features. These include the study of building elevations by Bovill (1996), the analysis of street elevations, street patterns and street vistas by Cooper (2000, 2008), the research on skylines by Stamp (2002) and Cooper (2003), the work on urban boundaries by Batty and Longley (2004), the study of visual preference and structural landscape by Gotou *et al* (2002) and Hagerhall *et al* (2004), etc (see also table 4.1 for more examples). Some also explored the notion of finding a kind of fingerprint for the configuration of shapes and structures of a city (Webster, 1995, 2005; Haghani, 2004).

However, most of these suggest fractal measurement as a critical tool evaluating an urban morphological feature without reference to its change and evolution over time. In other words, there is a relative lack of research so far addressing the application of fractal analysis in measuring the change in urban morphological complexity. For instance, Cooper (2000, 2003, 2008) investigated the potential chaos and fractal analysis in examining urban elements at the street level for the city of Oxford. He proposed the fractal analysis method for evaluating urban snapshots, and his focus was on physical form of the city, not the processes of change and evolution over time. Therefore, this thesis examines this less-researched area. It aims to develop a fractal analysis tool to measure the processes of change in morphological complexity, and to that extent, it focuses on assessing the change in urban patterns.

1.1.4 The fractal analysis of planned and unplanned/organic urban patterns

> 'All cities show some irregularity in most of their parts and are thus ideal candidates for the application of fractal geometry' (Batty and Longley, 1994, p.2).

Many analyses of urban form suggest that there are two types of urban patterns – '*planned*' and '*unplanned or organic*'. While planned cities, or the planned parts of them, are cast in the geometry of straight lines (Euclidean geometry), the immediate application of fractal geometry is to the latter type. However, city geometry is often more complex, marrying the two pure types in modulated and refracted combination (for example see figure 1.2). The close fusion of planned and unplanned, regular and irregular, elements leads to the assumption that the great majority of towns grow by an organic, piecemeal, unplanned process. Conversely, some morphologists (e.g. Slater, 1990a, 1999) believe that, what seems to be organic or unplanned is often the conjunction of 'many small phases of planning activity' (Larkham, 1996b, p.35).

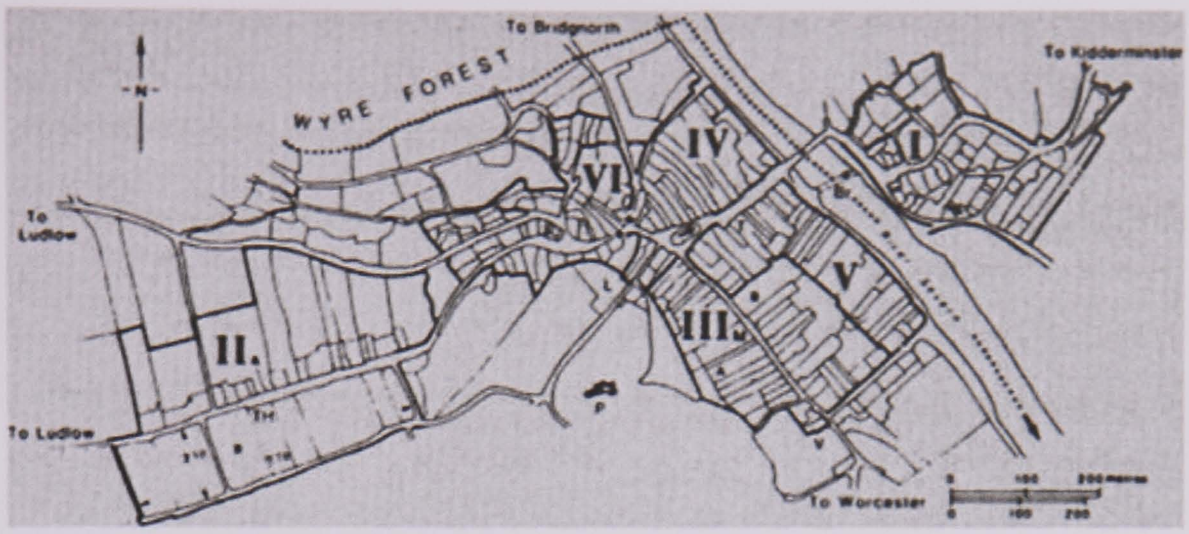

Figure 1.2: The plan of Bewdley. The analysis identifies six units of planned and unplanned phases of growth. (Slater, 1990a, reproduced in Larkham, 1996b, p.35)

Urban pattern analysis, in many cases, shows that what seems "unplanned" is actually the result of many phases of planning, some of which are geometric and regular. Moreover, less-planned encroachments over several centuries have affected the appearance of many places (Larkham, 1996b). However, even the planned parts of a city (e.g. Unit IV in figure 1.2) are adapted to their context in more unplanned/organic ways once the plan is implemented; and they evolve gradually according to new needs and conditions. Thus, in any case, the extent to which urban form is ordered or planned is always a matter of degree (Batty and Longley, 1994). Furthermore, even when buildings are marshalled like troops along straight lines of an urban grid, the animation in their mass and height resulted in picturesque formations believed to be congenital to the unplanned/organic city (Kostof, 1991). Therefore, all cities show some irregularity in most of their parts, and as Batty and Longley (1994) claim, they are all ideal candidates for the application of fractal geometry (see Chapter Two, section 2.2).

Another important point – seemingly terminological but actually based on the conceptual debate between urban morphologists – is to find an appropriate term for the gradually grown and evolved urban patterns. Some authors (e.g. Lynch, 1981; Kostof, 1991) prefer the term "unplanned," as the term "organic" might have biological connotations. They argue that the visual and functional analogies between a city and an organism – such as streets/veins, parks/ lungs, city centre/heart, etc – can be misleading. The confusion stems from the distinction that they assume to be fundamental between the city, as an artificial system, and the human, as the driver of urban form and function. Lynch (1981, p.95) writes that 'cities are not organisms.... They do not grow or change themselves, or reproduce or repair themselves'. According to him, human purpose drives the making of cities, whether planned or not.

The proponents of the term "organic" emphasise the systematic rather than visual analogies between cities and organisms, considering cities as open living not artificial mechanical systems. Referring to the opening statements of this chapter (section 1.1.1), complexity theorists believe that there is a strong inter-linkage between a city, its constituent parts, the socio-spatial forces and factors by which they can hardly be understood apart. Human activity at local scales and the emergent properties of the city at macro scales should be understood together in an inter-dependent complex system (see again figure 1.1). If the human activities are seen as part of the whole system, it can be argued that city systems have a self-organising nature.

In this sense, the term "organic" better represents the complex nature of urban change and its defining features (discussed earlier in section 1.1.1; see also Chapter Three, section 3.2.2). It also implies self-regulating, self-generating, and self-organising processes within city systems, while the term "unplanned" does not. Finally, the term "organic" conveys the notion of time and gradual change, which is the main property of naturally grown patterns. In this sense, "organic pattern," while perhaps may be not perfect, is the preferred term for the rest of this thesis – referring to the parts of cities gradually grown or evolved over time.

1.2 Aims, Objectives and the Research Questions

1.2.1 Aims and objectives

> 'Research aims are at the very heart of the thesis. Thus, they should be a thread, which links it together in expressing clearly and precisely the anticipated achievements of the original contribution to knowledge, which will be achieved' (Oliver, 2004, p.121).

With the range of issues described earlier, the principal aims supply a broad indication of this study. These are:

a) Identifying the achievements and failures of the geometry of straight lines (linear Euclidean principles) as applied to the conventional top down planning, architecture, and urban design

b) Introducing the principles and applications of complexity theory and fractal geometry in order to examine their potential in urban morphological and functional analysis

c) Examining the potential of a fractal assessment methods to measure and map urban morphological complexity

The research objectives are:

a) Developing a fractal assessment tool to identify, classify, and analyse emergent urban patterns originating from both organic and planned types of growth

b) Selecting an area where historical data and record are available, and then assessing the fractal dimensions of its neighbourhoods to measure mathematically the change in its physical complexity

c) Producing a fractal map as a tool for architects, planners, and urban designers enabling them to reflect better on their design proposals and decisions before their real implementation

1.2.2 The research questions

Two set of questions will be explored to achieve the research principal aims and objectives. The first set is general but includes important questions related to complexity and the nature of urban morphological evolution. These questions will respond to the main aims of the research:

1. Why can Euclidean geometry and its linear principles not explain urban morphological complexity?
2. What does complexity theory mean? What is its relationship with chaotic dynamics and fractal geometry? What are the properties of complexity by which a complex system can be identified? Moreover, does a city system demonstrate these properties?
3. Is fractal geometry an essential substitute for Euclidean geometry as applied to architecture and urban design?
4. Why does the conventional top down approach to planning and urban design not conform to the nature of urban morphological evolution?

The research will then focus on the specific questions to achieve its objectives. The second set explores the applications of complexity theory and fractals as related to city form and function to devise a more accurate tool for spatial and morphological analysis. The questions are:

5. How may complexity theory and fractal geometry be applied to urban planning and design?
6. How could urban physical complexity be measured, visualised, and mapped?
7. How can fractal dimension be referred as a criterion to identify, classify, and analyse the change in complexity of urban patterns?

1.3 The Research Methodology

> 'Quantitative research is considered to be hard-nosed, data-driven, outcome-oriented, and truly scientific' (Yin, 2003b, p.33).

The research aims to develop a fractal analysis tool in order to assess the change in urban morphological complexity, not to evaluate them. Therefore, it follows a quantitative methodology rather than a qualitative one. Furthermore, since this research is of the data-driven, outcome-oriented type, a case study strategy is appropriate. Yin (2003a, p.1) writes:

> 'Case studies are the preferred strategy when "how" or "why" questions are being posed, when the investigator has little control over events, and when the focus is on a contemporary phenomenon within some real-life context.'

Therefore, among five different possible methods (experiment, survey, archival analysis, history, and case study) suggested by Yin (2003a), the "why" and "how" questions presented in the previous section are appropriate for the case study method. According to this type of strategy, the research should define an appropriate case study, and determine the relevant data to be collected and analysed.

1.3.1 The case study

Tehran, the capital city of Iran, provides good sample cases to be studied. Morphologically, the city is the product of two different patterns of growth. On the one hand, a fast large-scale expansion of the city imposed its regular grid-like pattern on the suburban areas. On the other, the gradual growth of the villages –formerly encircling the city gradually converted to be significant centres inside the city –generally produces organic patterns. This rapid growth, when merged with gradual transformation of the suburbs, provides very complex urban patterns in the neighbourhoods around these centres. Tajrish, the centre of Shemiran – a district located in the north of Tehran – has such characteristics, as it demonstrates the contradiction between both patterns of growth.

Chapter Five provides a detailed explanation of the criteria that have been considered for selecting an appropriate case study and the required sample cases. The fractal analysis method employed in this research aims to measure the degree of change in the complexity of urban patterns at different neighbourhoods in Shemiran. If this method is found to be useful for the selected sample cases, then the same method can be used for the entire city of Tehran and other cities too.

1.3.2 The thesis structure and the stages of the investigation

The research comprises three main stages, a) the literature review, b) the data collection and examination, and c) the data analysis. At each stage, the strategy is to narrow down the research according to its main aims, and to focus on the target specified by the research objectives. In this section, three stages of the investigation are briefly introduced. Figures 1.3, 1.4, and 1.5 illustrate the key elements of each stage.

1.3.2.1 Stage I, the literature review:

This aims to investigate the traditional and conventional approaches towards urban form, providing the platform for the application of the fractal concept. Firstly, the review intends to identify the traditional views of urban form, and particularly, it discuses the role of the science of Euclidian geometry in shaping urban form throughout history (Chapter Two). Secondly, the properties of fractals, complexity, and chaos theories will be reviewed in order to identify how these new theories provide a more realistic insight into the study of urban form and change (Chapter Three). The advantages of fractal approach for understanding of urban complexity will be highlighted in order to shift our views from the top down deterministic planning and design tradition to the more realistic and flexible bottom up approach (Chapter Four).

By the end of the literature review, a number of approaches in the application of fractal theory in the study of urban form, growth, and change will be outlined to provide a backbone for the empirical stage, where the research aims to develop its own fractal analysis tool. As shown in figure 1.3, the research will be narrowed down, at this stage, from relatively a wide literature to a focused target, refining the research method for the empirical stage.

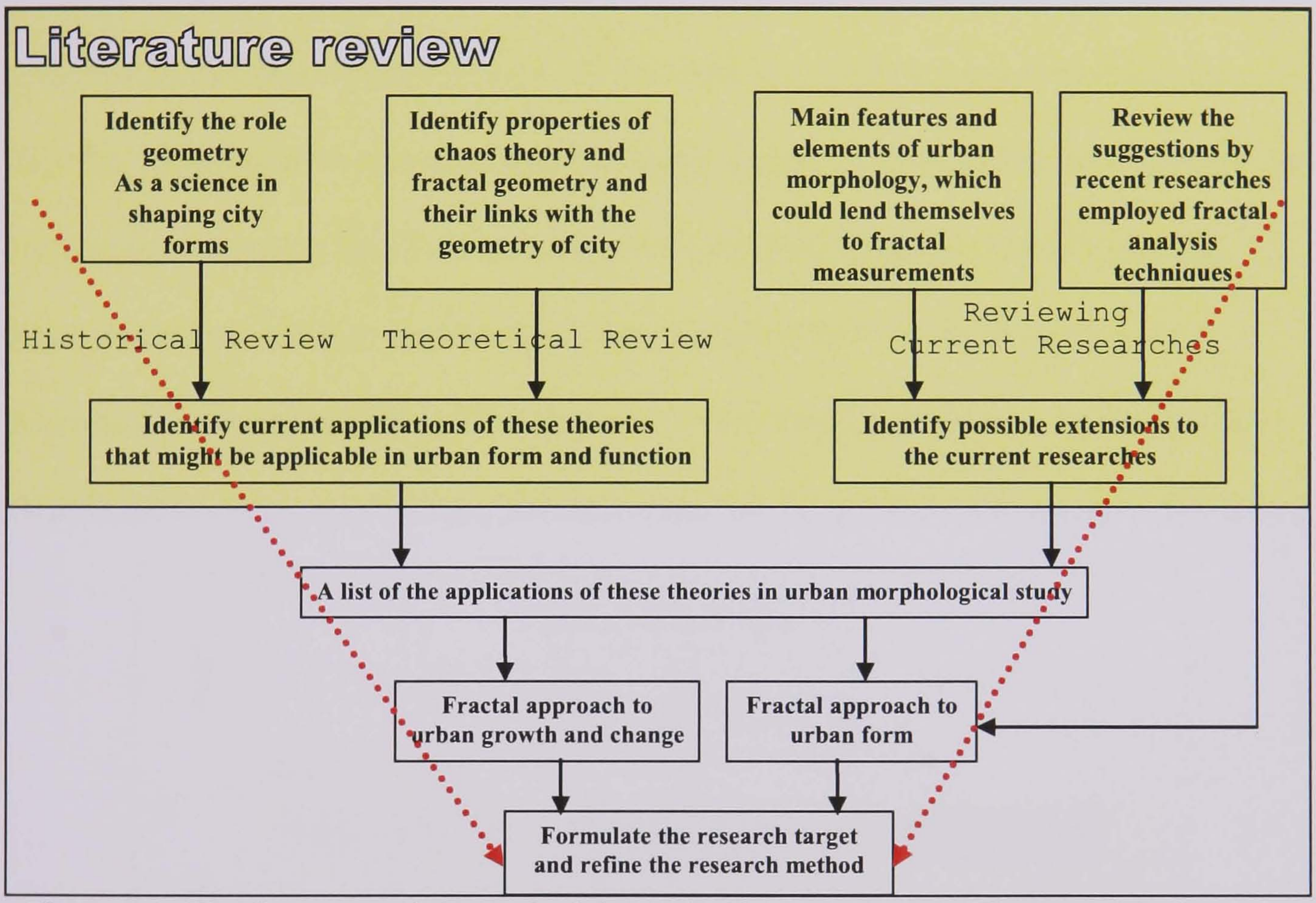

Figure 1.3: The first stage of the methodology; the literature review. The arrows indicate the overall strategy to narrow down the research and to formulate its target.

1.3.2.2 <u>Stage II, the data collection and examination:</u>

Once the research has indentified its target, it follows three sequential steps at the empirical stage including case study selection (Chapter Five), pilot study, and case study examination (Chapter Six). The first step defines the relevant case study and sample cases to be examined according to the research target. The advantages of using remote sensing city images, as the data source, will be identified (Chapter Six, section 6.1.1). Then, the research develops its fractal assessment tool by using two different software programs in linkage. It employs Benoit 1.3 (fractal analysis software) to facilitate fractal dimension calculation and ArcMap 9.2 (GIS software) for its mapping, layer-overlapping capabilities. The latter software will convert numerical data into pictorial data in order to visualise spatial fractal dimensions in terms of the fractal map. The rationale for using this software is given in Chapter Six (see section 6.1.4.2).

The important step at this stage is to test the reliability of the method before it is applied to the main case study. Therefore, at the second step, the pilot study carries out two different tests (Chapter Six, section 6.2). The first is the validity test, which aims to calibrate the adjustable parameters of the fractal analysis software. The second test is the sensitivity test, which checks urban elements within the image contents in terms of appropriateness, and the consistency of the pictorial data in terms of resolution, brightness, and contrast. The aerial photos of the selected case study are processed and refined based on the result of the pilot study and are prepared for the actual examination.

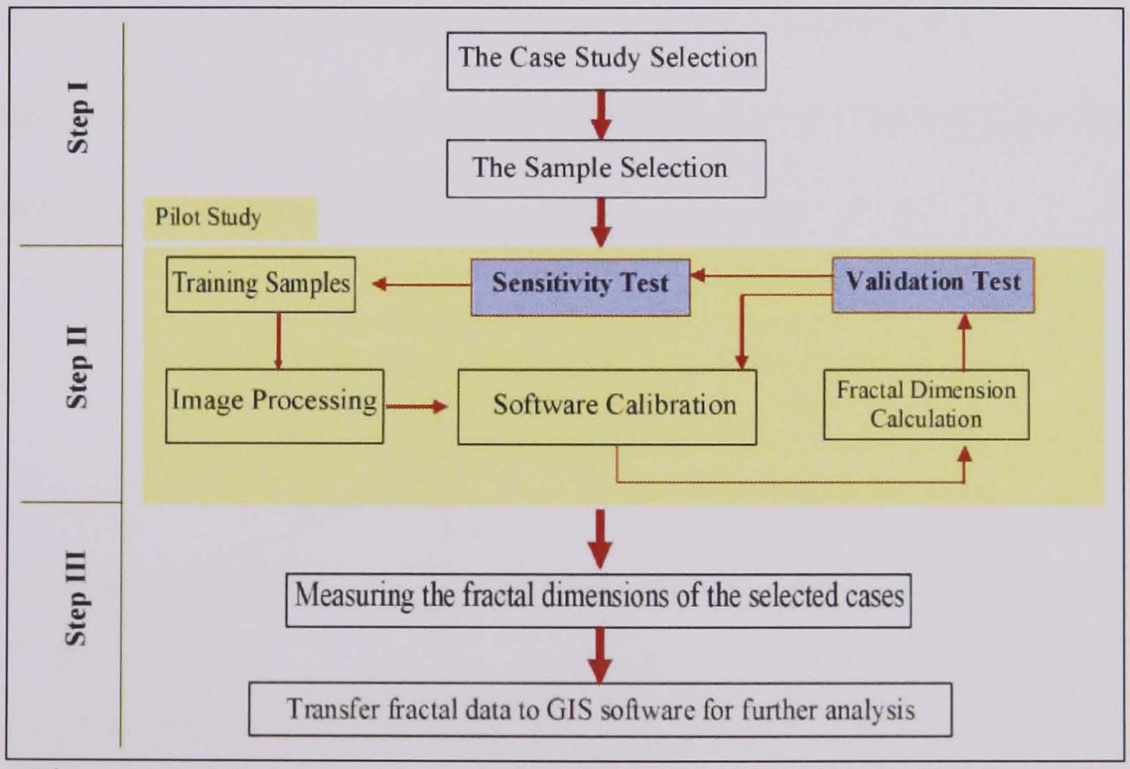

Figure 1.4: The second stage of methodology; the data collection and examination. The second stage of investigation includes the case study and sample selection, the pilot study; and the case study Examination.

The third step carries out the fractal measurement of the case study and the selected samples (Chapter Six, section 6.3). The aim is to assess the fractal dimensions of the selected areas from the neighbourhood local scales to the district and city scales. Since the focus of the research is at local scales, further examination will be carried out at neighbourhood level of the case study to measure the change in the complexity of their urban patterns for the period from 1956 to 2002 (determined by the availability of aerial photographs). The result of these measurements will be processed into the GIS software to be mapped. Figure 1.4 illustrates the main steps that are to be carried out at the stage II.

1.3.2.3 Stage III, the data analysis:

The numerical data from the previous stage is transferred to GIS software (ArcGIS) in order to be visualised, mapped, and analysed (chapters Six and Seven). The map produced suggests a kind of fractal fingerprint for the examined neighbourhoods. This, together with the proposition of the fractal Identification code (FNID), provides the base for the pattern analysis at the third stage (Chapter Seven, section 7.1). The method will facilitate the pattern recognition and classification based on the degree of complexity that different neighbourhoods pose. The fractal map also identifies the homogeneity/heterogeneity of urban patterns and the areas that the urban patterns begin to be transformed or distorted (Chapter Seven, section 7.2).

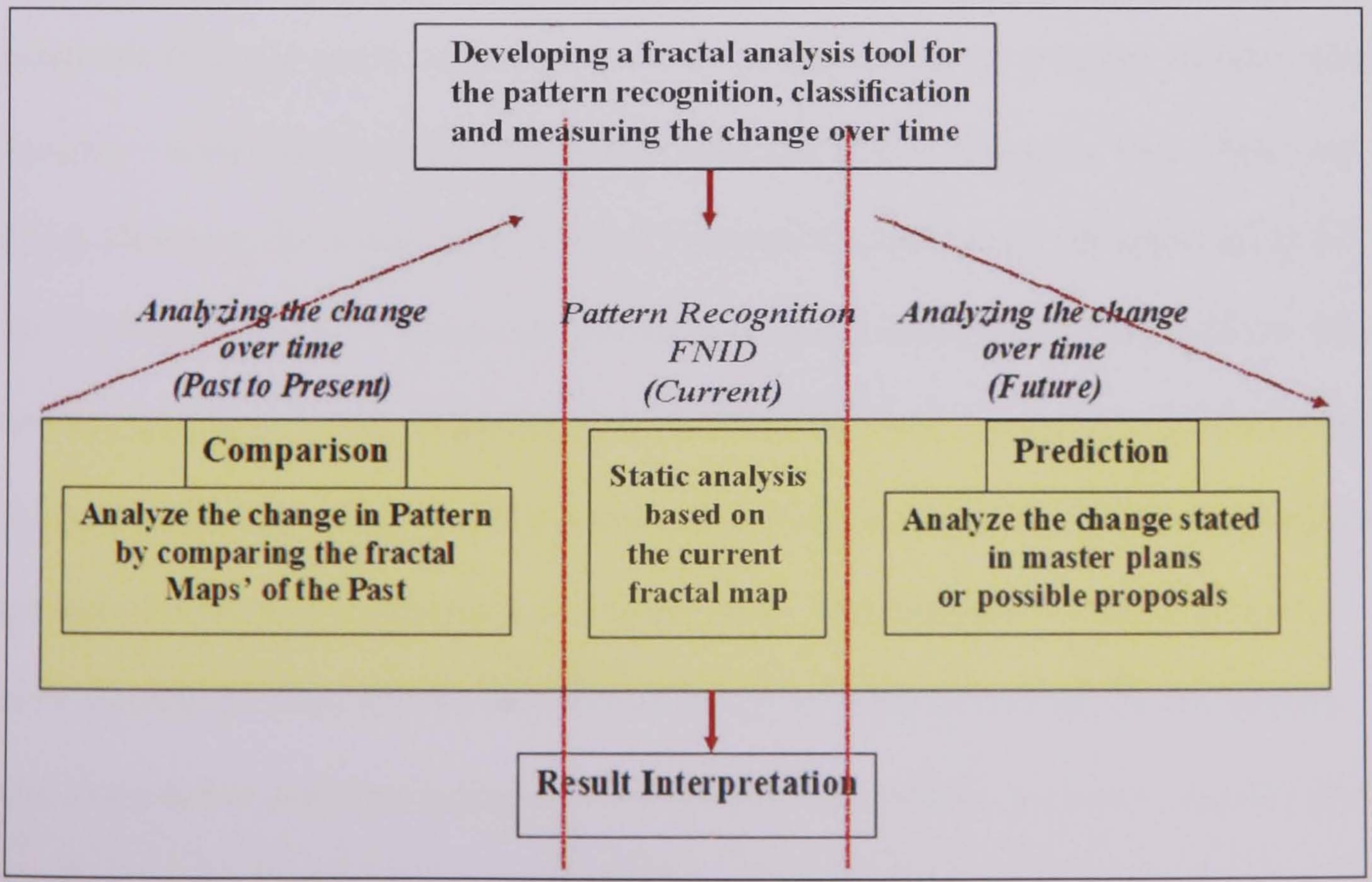

Figure 1.5: The third stage of methodology, the data analysis. It includes the pattern recognition, classification and measuring the change over time.

Moreover, several maps from past to present are compared in order to measure the degree of change in physical complexity of the selected samples overtime (see Chapter Seven, section 7.3). This comparison will reveal the degree of impacts that urban interventions have imposed on physical complexity of selected case studies. Finally, the potentiality of proposed fractal technique in analyzing future morphological changes will be addressed. At this point, the fractal signature (FNID) of each neighbourhood provides a benchmark for testing different urban scenarios according to the current planning policies, possible architectural proposals, or urban design projects (see Chapter Seven, section 7.3.2.1). Figure 1.5 illustrates the main ideas that will be discussed at data analysis stage.

1.4 Chapter Summary

The introductory chapter highlighted the research main theme and outlined the key researches supporting the topic, the less-researched areas, and the focus of the thesis. It also introduced the research aims and objectives by which two set of questions were formulated. As discussed in this chapter, the first set targets the research aims – the potentials of fractal geometry as compared to Euclidean geometry in urban morphological analysis – which are achievable through the literature review (Chapters Two, Three, and Four). However, the second set focuses on the research objectives – the applicability of the fractal analysis tool – which requires the case study examination (Chapters Five, Six, and Seven). Chapter Two, in particular, reviews the literature through a historical context to examine the role, strengths and weaknesses of the geometry of straight lines (Euclidean geometry) in shaping architectural and urban forms. The literature review, in general, aims to establish some reasons why understanding of urban morphological complexity and its evolution over time is beyond the principles of Euclidean geometry, and therefore, it requires some further knowledge in the light of complexity theory and fractal geometry.

CHAPTER TWO

THE CONVENTIONAL GEOMETRY OF STRAIGHT LINES

Introduction

While there are several directions in which urban evolution can be examined based on complexity and fractal theories, this research focuses on geometrical rather than functional aspects. Therefore, this chapter takes the first step in focusing the research by identifying the advantages of fractal geometry in comparison to conventional Euclidean geometry in urban morphological analysis. In the first part of the chapter, the geometry of straight lines as applied to architecture and urban form will be interpreted. In the second part, the strengths and weaknesses of such geometry will be discussed.

The chapter attempts to review the significance of geometrical approaches towards the built environment in various historical periods. This brief review does not cover the history of urban forms, instead aiming to emphasise how developments in the science of geometry have equipped humans with a mathematical tool to conceptualise their environment; and highlighting how the geometry of straight lines – known as Euclidian geometry – governs the way we think and build our cities. It will then be argued that even though this geometry has gained success in some aspects of architecture and city design through history, it has failed to describe the substantial complexity that exists within the city fabric; hence a new theory of urban form and growth is required that can explain more accurately how cities develop and should be developed. In this sense, the main goal of this chapter is to establish the reasons why new insights into the evolution of urban form require some knowledge of complexity and fractal geometry.

2.1 Part One: The Implications and Interpretations of Euclidean Geometry as Applied to Architecture and Urban Form

2.1.1 The origins of geometry and its role in shaping the built environment

> 'There is evidence that man always made sense of the world through powerful simplifying abstractions which seek out the underlying principles and order in our experiences and perceptions' (Batty and Longley, 1994, p.10).

According to Batty and Longley (1994), humans have sought such abstraction to simplify the world visually and impose a smooth geometry on art so that its meaning can be communicated in the simplest and the most effective way. In fact, the science of geometry has enabled people to define their relationships with their natural and built environment, by measuring spaces and objects within nature and consequently reflecting their perception and interpretation on what they created such as paintings, sculptures, handicrafts…, as well as buildings and cities.

Human kind ------ Geometry ------------ Nature

Based on archaeological evidence, today we know that humans attempted to devise a simple geometry describing natural phenomena (Janson, 2001). This geometry enabled them to simplify and abstract the natural environment into simple lines, circles, and dots. This also assists them to make a sense of their environment by measuring the size and distance of objects and comparing their proportions (Gardner, 1970). This can be observed in cave paintings (15,000 – 7000 BC) and the primitive tools and crafts remained from them during this period. Stone Age cave paintings revealed a primitive way of symbolizing nature in very simple geometrical signs (figure 2.1). Humans employed geometry in many ways such as: describing natural shapes, creating symbols for visual communication, expressing belief, emotion, metaphysical metaphors, and imposing mathematical order to define territories and in shaping his built environment.

Figure 2.1: The above cave paintings found shows that man improved his ability from naturalistic perception of nature (Left, Dordogne, France, 15,000-10,000 BC) to more abstract signs imbedded in rectangular format (Right, Standard of Ur, Mesopotamia, 2600 BC). (Left, Gardner, 1970, p.16; Right, Janson, 2001, p.67)

Nickolas Salingaros (1997, 1999, 2003, 2005), a mathematician with a broad interest in the conceptualization of fractal geometry, believes that 'geometry' as one of two main branches of pre-modern mathematics could provide a universal grammar for architecture. He states that geometry explains the role of detail, colour, decoration, matching shapes, repetition of units, etc; and in traditional architecture, it was a vocabulary for achieving coherence. He states that, in the past, the relationship between mathematics and architecture was two-way, reinforcing, and mutually beneficial (Salingaros, 1999). Symmetry, mathematical proportion in the Renaissance architecture (e.g. Alberti's work), and the Golden Section in classical and humanistic architecture, are some examples of this key mutual relationship. The next section elaborates some of these examples to highlight the role of the science of geometry in shaping the built environment through history.

2.1.2 A brief history of geometric implications for architecture and urban form

2.1.2.1 Geometry of antiquity:

> 'There is no sense in the written record of any time when man's spatial sense of order was less developed than in modern times, although the association of geometrical order with science and with the means to impose that order through technology has changed substantially since the first urban civilization emerged' (Batty and Longley, 1994, p.11).

In the long history of city forms and shapes from western Asia and Mesopotamia to today's new towns, the science of geometry has played an outstanding role. While most early settlements are marked by 'natural' or 'organic' growth (figure 2.2, left), there are some examples of 'planned' developments where a simple but precise geometry was employed (Morris, 1994; Kostof, 1991). From the earliest settlements, people have sought to impose the notion of visual abstraction and pure geometry on both natural and artificial phenomena such as towns. The Babylonian city of *Ur*, the Egyptian city of *Tel-el-Amarna*, *Kahun*, *Mohenjo-Daro* in the *Ancient Indus Valley*, etc, all had elements of geometrically ordered streets and buildings and some followed gridiron plans (figure 2.2).

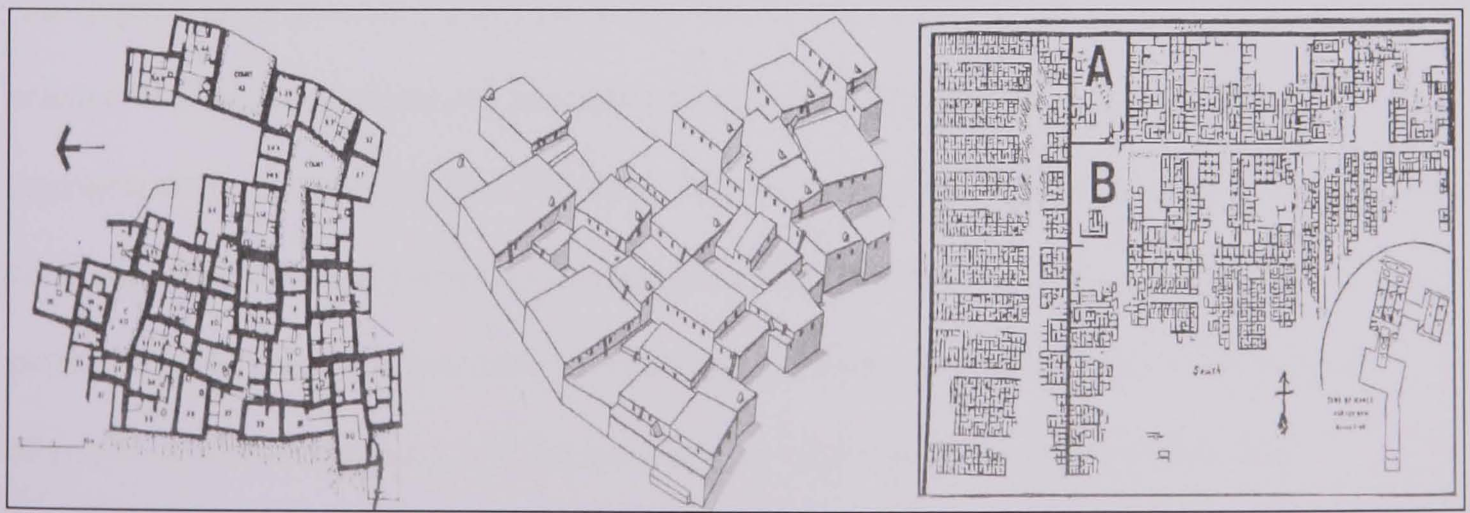

Figure 2.2: Geometry of early settlements; the organic plan and schematic reconstruction of *Huyuk* in Mesopotamia (left and middle) as compared to the gridiron plan of *Kahun* in ancient Egypt (right). (Middle, Gardner, 1970, p.32; Left and right, Morris, 1994, pp.19, 29)

There is no doubt that the Egyptian civilization was also clearly aware of the science of geometry, by which they divided agricultural lands, measured the boundaries of the annual floods of the Nile and so on. The Egyptians considered the world to be a flat plane and that the river Nile passed through its centre. In the Egyptians' mind, the line from the South to the North was drawn by the river while the East-West direction was defined by the sun, the four basic directions that inspired them to orientate their buildings. Records also show that they were clearly aware of the Pythagoras's 3-4-5 proportion to create a perpendicular line by which their buildings such as the Pyramids obeyed precise geometry (Bianca, 2000).

However, it was the Greeks who first founded the philosophical approach towards the science of geometry and developed it to plan and build their cities. A long line of Greek scientists and geometers (e.g. Pythagoras, Plato, Aristotle and Euclid) assembled a science that ultimately provided the foundation for later civilizations. They developed our visual senses to the point where 'art and science came to be treated as one', and where 'the imposition of geometry upon the nature was first interpreted though the medium of science' that has been continued ever since (Batty and Longley, 1994, p.11). While scientists such as Aristotle (*circa* 384 BC – 322 BC) contributed to the key ideas and concepts of understanding and classifying nature, Euclid (*circa* 325 BC–265 BC), in particular, established the geometrical principles and forms which dominated the history of architecture, city planning, and design – known as Euclidean geometry (Pearson, 2001).

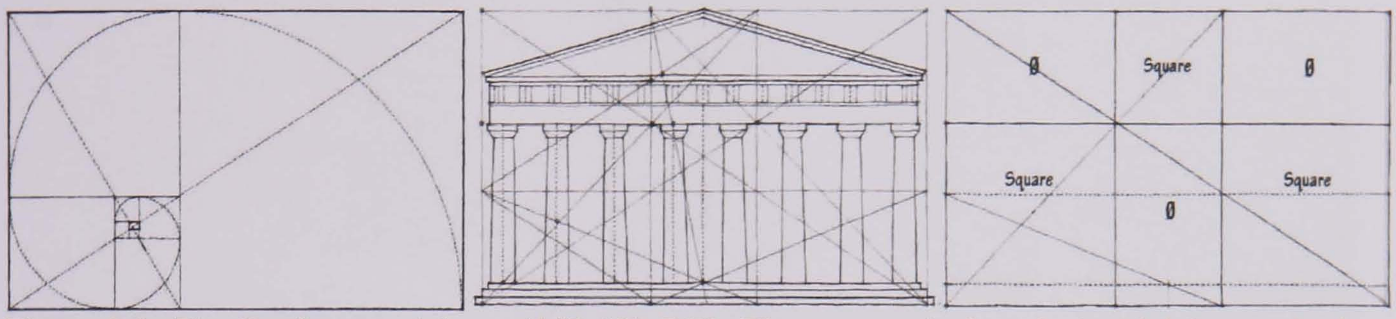

Figure 2.3: The Parthenon, Athens (447-432 BC). The geometrical analysis (right) reveals the effect of 'Golden Section' (left) on the distribution of elements across the façade (middle). (Ching, 2007, pp.303-304)

In architectural terms, as Ching (2007) describes, the Greek public buildings obeyed precise proportions (e.g. golden section, figure 2.3) based on the belief that certain numerical relationships manifest the harmonic structure of nature (the Pythagorean concept, see 2.15, left). In urban terms, however, ancient Greeks (before 400 BC) tended to create a harmonic relationship between the city form and its natural terrain (e.g. Athens, figure 2.4).

According to Benevolo (1980), this concept was applied to early Greek cities, particularly those before the classic and Hellenistic eras, where houses developed organically around public places and followed natural topographical features of the nature. Although each individual public building within an *agora* (Greek public space) obeyed a pure and proportional geometry, their composition at the city scale did not violate the organic features of the terrain. Therefore, it can be claimed that the structural and organizational order of the city as a whole 'was not the result of any fixed forward planning policy', but the result of 'the process of self-improvement' (Benevolo, 1980, pp.71-72).

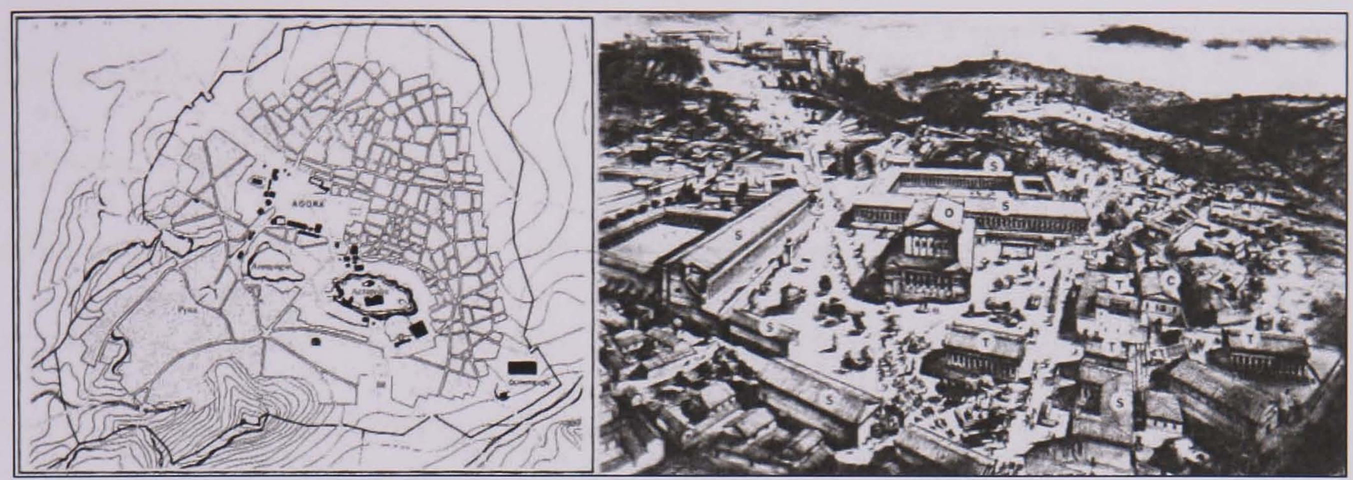

Figure 2.4: Athens' rough plan and a view of its *agora* during the Roman period which reveals its geometrical harmony with natural features. (Benevolo, 1980, pp.92-94)

In the case of Athens (figure 2.4), for instance, Benevolo (1980, pp.60-72) described the geometrical characteristics of the city as follows:

> 'Neither the streets nor the walls nor the monumental buildings succeeded in concealing the natural contours... and the lines of the countryside.'

While this is relevant for the early Greek cities such as Athens and Delos, evolving and growing gradually without planning, there was a group of cities, reconstructed later in the classic era (480 BC – 323 BC) such as Miletus and Priene (figure, 2.5), which had defined plans with specific divisions created by a regular geometry. The latter group manifested clearly a shift from philosophical approaches to analytical and socio-political views toward geometry and its role in city planning and design.

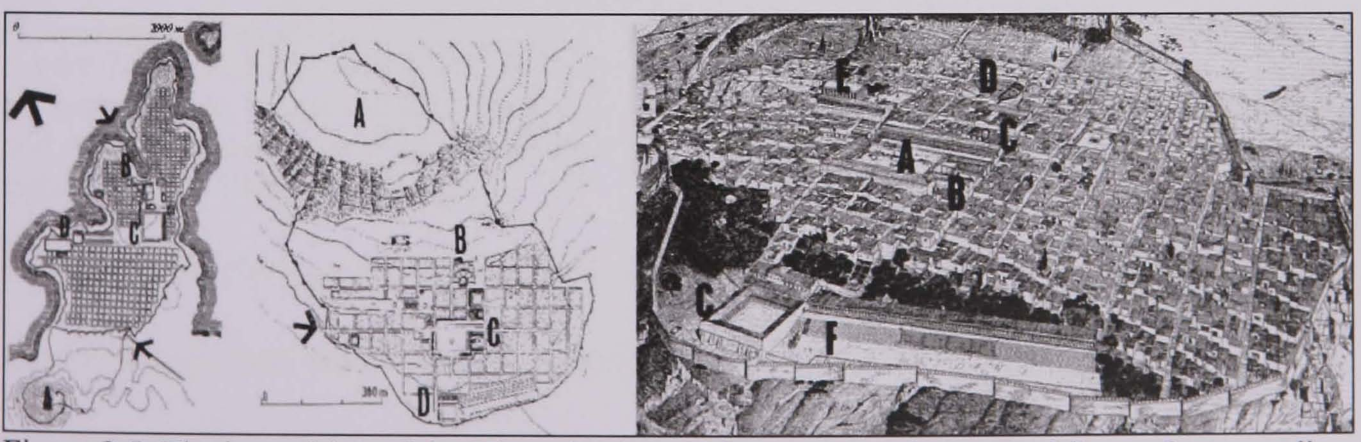

Figure 2.5: The imposition of the Hippodamian grid – as opposed to natural lines of surrounding nature – in Miletus (left) and Priene (middle, and right). (Morris, 1994, pp.43-45)

The influential idea of the gridiron layout was developed by one of the first known city planners, 'Hippodamus' (*circa* 498 BC–408 BC). He proposed a city plan that featured order and regularity, in contrast to the intricacy and complexity that were more common in earlier Greek cities, and he is called the originator of the idea that a town plan might formally embody and clarify a rational social order (Morris, 1994).

The Romans moved on from Greek philosophy of geometry to practice. The influential work by Vitruvius (*circa* 80 BC – 15 BC) developed the science of geometry to a more functional level at both architectural and urban scales. His '*homo quadratus*' – the figure of a man with extended arms and feet (figure 2.6, left) – fit neatly into the square and circle which were considered the most perfect geometrical figures (Ching, 2007). The Romans found that these two shapes are structurally stronger and more economical than earlier straight post and beam designs, hence which they developed arches, vaults, and domes (Pearson, 2001).

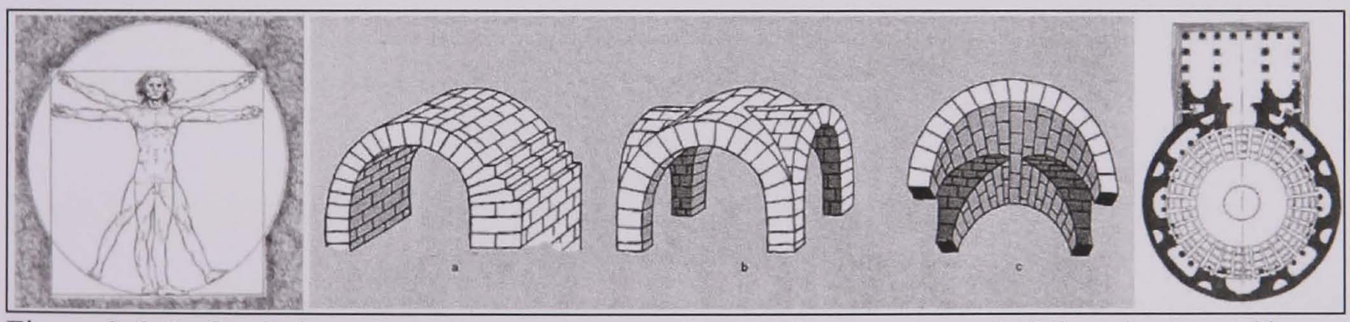

Figure 2.6: Left, circle and square were assumed as perfect geometry in Vitruvian man (drawn by Leonardo da Vinci); Middle, three types of Roman vaults based on combination of circle and square; Right, plan of the Pantheon, 118-25 AD. (Left, Ching, 2007, p.292; Middle and right, Gardner, 1970, pp.211-212)

At city scales, the Romans established a series of military towns and camps (called *castra*) within their vast empire to be able to control their territories. The main structure of a Roman camp obeyed a simple rectangular geometry created by two perpendicular long streets (*decumanus* and the *Cardo*) with the emphasis on certain buildings (e.g.

basilicas) or monumental elements (e.g. statues). This regular urban layout facilitated military movement (figure 2.7). Further to the functional purposes, the geometrical prototype of this model was a way to express the dignity and power of the empire. The pure, straight, and powerful geometry became the master plan of many colonial cities after they had been conquered by the Romans, which implied the dominant unity of the Romans across their territories (Mumford, 1961).

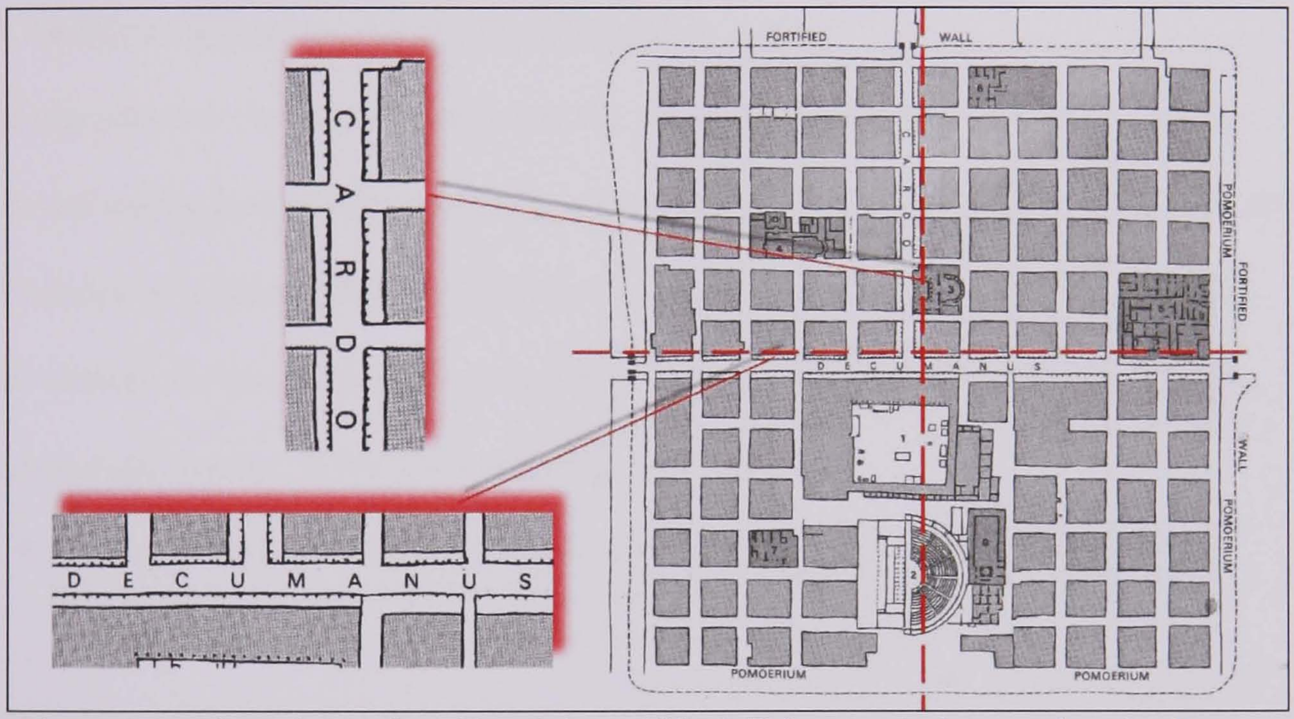

Figure 2.7: Timgad, North Africa (*circa* 100 A.D.); a typical example of a Roman *castra*. (Gardner, 1970, p.205; annotated by the author)

Vitruvius is well known not only for his significant contributions to the field of architecture and city planning, but for inspiring and motivating other artists and architects in the early Renaissance. His significant work *'De Architectura libri decem'* (Ten Books on Architecture) is the only complete treatise on arts, architecture and urbanism to survive from classical antiquity (Encyclopaedia Britannica, online, undated). In this book, he outlines fundamental considerations to be observed in designing towns and describes the features of a city laid out on a circular plan (figure 2.19). 'His ideas were not, however, illustrated by an actual plan… and this is a form never used in practice by the Romans for any of the countless military camps and towns they established throughout the empire' (Morris, 1994, p.169). Nevertheless, it can be claimed that Vitruvius himself was advocating theoretically the concept of ideal city, which later influenced on the Renaissance planners who developed his idea.

2.1.2.2 Divine geometry of dark ages (the Middle Ages):

The gap between classical antiquity and the Renaissance was regarded 'as a thousand dark and empty years' (Gardner, 1970, p.368). During this period (*circa* 400–1400 AC), the science of geometry did not make any significant progress, instead, it was shifted from humanistic and naturalistic philosophy towards a divine state of mind under Christian spirituality. In architectural terms, it means:

> 'You make each building in a way which is a gift to God. It belongs to God. It does not belong to you. It is made to serve God, to glorify God. It is not to glorify you. Perhaps, if anything, it humbles you' (Alexander, 2004, p.304).

While some elements of mystical and mythical interpretations have been established by earlier civilizations (e.g. the Egyptians and the Greeks), divine geometry was enhanced through the "Early Medieval", "Romanesque", and "Gothic" periods (Pearson, 2001). During these periods, mathematics and abstract geometry were considered the only appropriate expression of order and perfection created by God. For instance, in the Byzantine Empire, architecture was re-inspired with the ideas of divine proportion and mystique of numbers, and developed the Roman form of a dome placed on a square to create the typical Byzantine cross-in-square church plan (figure 2.8, left) and the Roman Basilica to the cross-in-rectangular plan (figure 2.8, right).

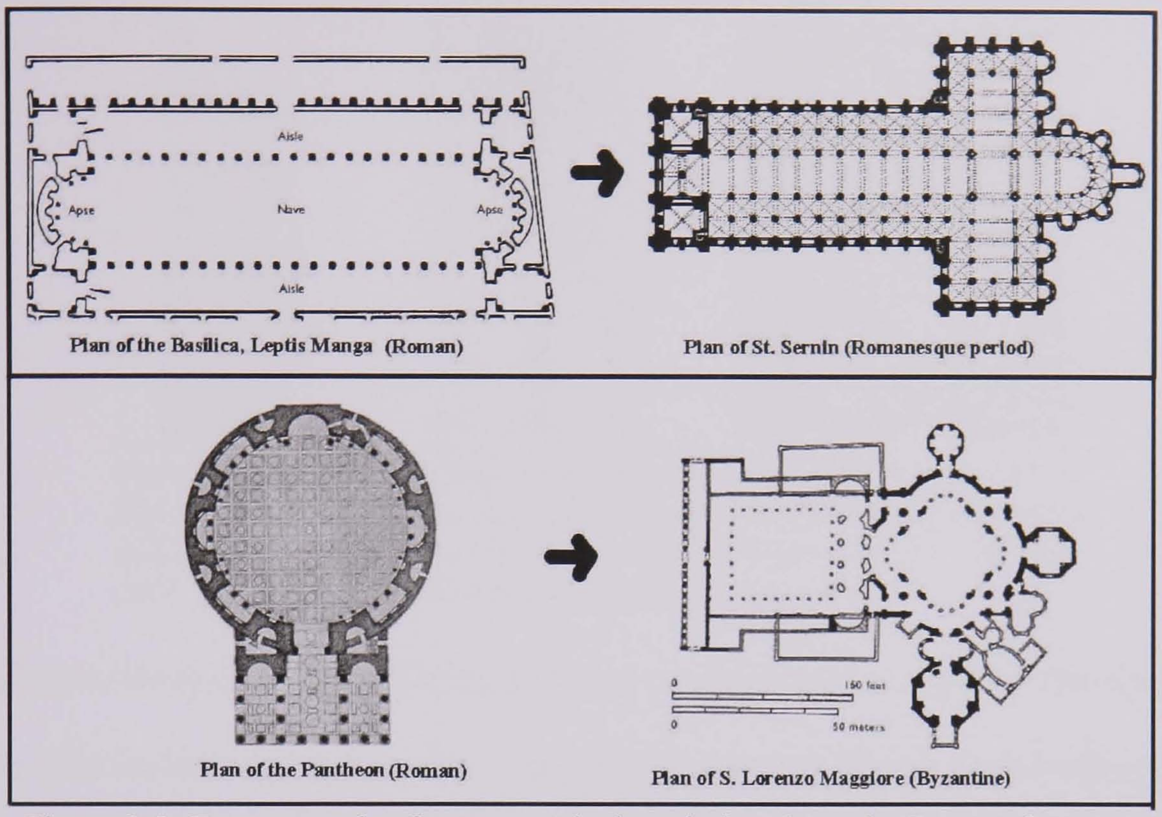

Figure 2.8: Two examples for geometrical evolution from the Roman forms to Byzantine and Romanesque churches. (Janson, 2001, pp.164, 167, 218, 276)

The line of evolutionary change in church architecture continued during the Gothic period where the application of the rib vault and the pointed arch provided a sophisticated architectural technique. Figure 2.9 shows how the geometrical difference between the Romanesque and the Gothic vaults resulted in a lighter, more flexible structural system. One of the characteristics of this system is its emphasis on the height with the columns and arches featured by several vertical lines (figure 2.10, middle and right).

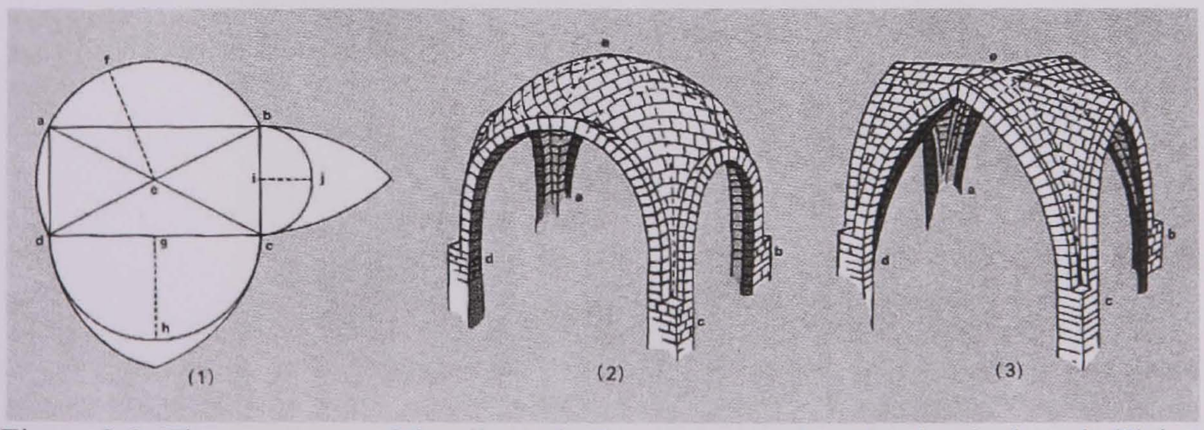

Figure 2.9: The geometry of the rib vault (3) as compared to the domical vault (2) is a lighter more flexible system, affording ample space for large windows. While the height of the semi-circular arch depends on the width of the vault (1) the pointed arch can maintain the same height with varied vault width. (Gardner, 1970, p.332)

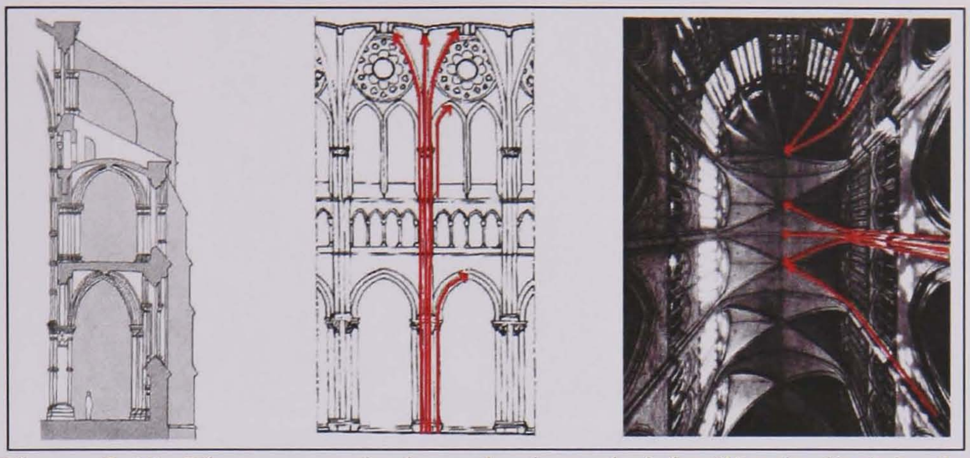

Figure 2.10: The geometrical emphasis on height (Verticality) in the Gothic architecture. The buttress structure (left), the Nave elevation of Chartres (middle), and the choir vault of Amiens (right). (Janson, 2001, pp.313-314, marked with red arrows by the author)

According to Bony (1983), the Gothic architects used height and light to obtain a feeling of aspiration toward God and heaven. They did this through the use of pointed arches, rib vaults, and the creative wall supporting system called 'flying buttresses' by which the weight of the building is placed on outside supports (figure 2.10, left). Since the walls were freed from bearing the weight of the ceiling, they could be designed with large openings. Artists filled these openings with the stained glass – tiny pieces of coloured glass fit together to form images which told the stories of Jesus and the saints. According to Bony (1983), 'Lightness' and 'colour', together with 'tall vertical elements' give the worshiper an image of the Heaven, an experience of the other world (figure 2.11).

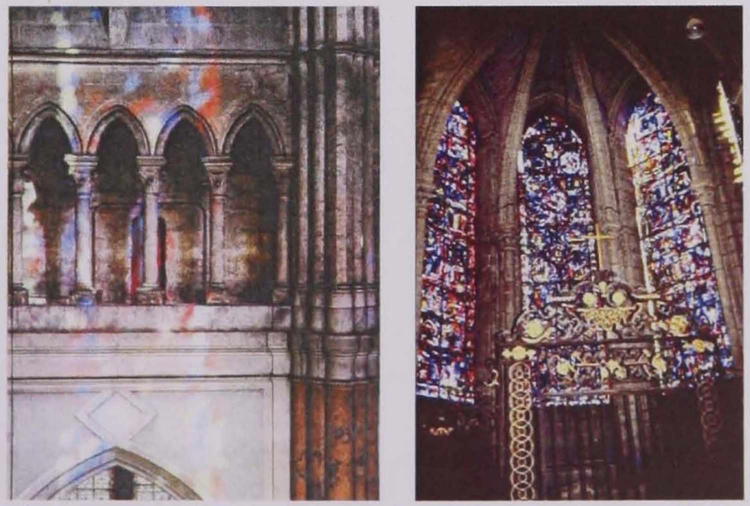

Figure 2.11: Chartres Cathedral's interiors; light, colour, and verticality in the Gothic architecture. (Left, Janson, 2001; Right, Branner, 1969)

Figure 2.12: The geometrical dominance of the medieval cathedrals at city scales: a) a model of Mont St Michel; b) Siena, an aerial view of the city centre and the Piazza del Duomo; c) St Mark's Square, showing the Palace and the Cathedral. (Benevolo, 1980, pp.307, 321)

Divine geometry had an impact at city scales too. The form of many medieval cities (e.g. figure 2.12, left) can be described as compact but nevertheless irregular, where buildings sited around central market square and church, following the form of the terrain (Lorenz, 2003). It can be claimed that there was geometrically a monumental competition in the townscapes of that time period between the cathedrals and the palaces associating with two social groups – clergy and aristocracy (e.g. figure 2.12, right). However, in the most cases, the glory and the height of the cathedral are a dominant element in the skyline of the medieval city (Mumford, 1961). It is this background that Le Corbusier describes in his book – written in 1937 and entitled '*When the Cathedrals were White*' (quoted by Benevolo, 1980, p.312):

> '… Above all the cities and towns encircled by new walls, the skyscraper of God dominant the countryside. They had made them as high as possible, extraordinarily high. It may seem disproportionate in the ensemble. Not at all, it was an act of optimism, a gesture of courage, a sign of pride, a proof of mastery! ...'

Urban historians (e.g. Mumford, 1961; Kostof, 1991), however, believe that the theories of absolute proportion lost their original significance in planning cities during the Meddle Ages. A fair summary of the situation was given by Paul Zucker – the author of "Town and Square" – that 'except in the comparatively few planned towns, the organization of a town as a whole was neither understood nor desired by the builders of the Middle Ages' (quoted in Morris, 1994, p.102).

According to Morris (1994) and Benevolo (1980), medieval cities mainly did not obey a regular predetermined plan, and even some cities originated from the Hippodamian schemes or the gridded Roman colonies gradually transformed into less regular and randomly oriented patterns (see figures 2.13, and 2.14). There are, also, several medieval new towns (e.g. the bastides) or 'medieval planned extensions', which started out from a gridiron plan subsequently underwent uncontrolled expansion and change' (Larkham *et al,* 1991, p.44; and Morris, 1994, p.92). It can be claimed that the initial geometrical order in the layouts of this type of medieval cities is due to the convenience of gridiron implementation rather than scientific or philosophical planning purposes.

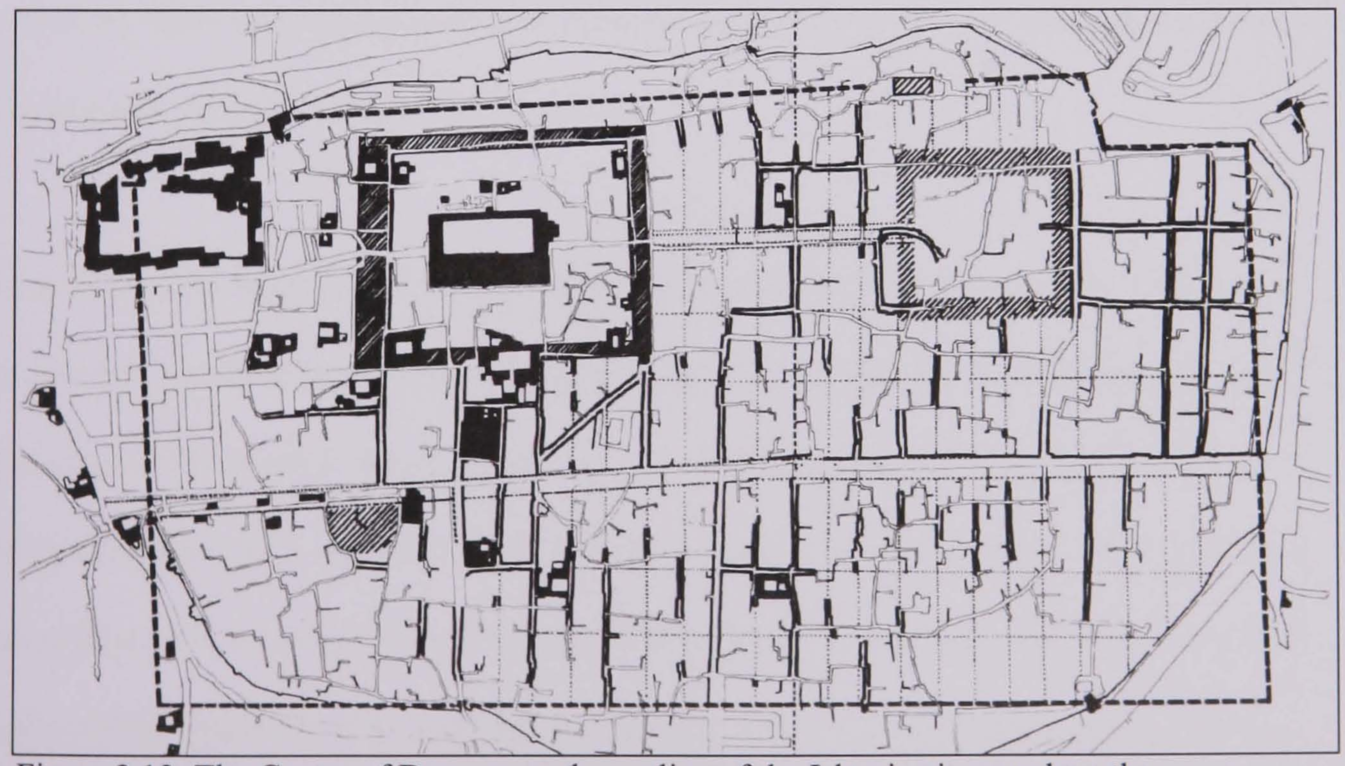

Figure 2.13: The Centre of Damascus; the outline of the Islamic city overlays the Hippodamian scheme of the Hellenistic city – marked by dotted and dashed lines – changing its geometricality. (Benevolo, 1980, p.260)

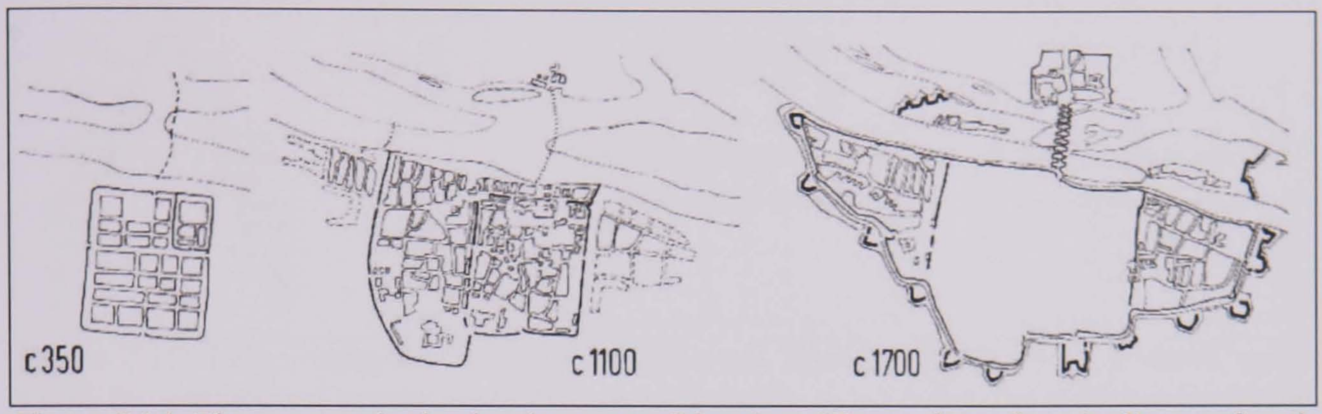

Figure 2.14: Three stages in the development of the city of Regensburg from its Roman frontier *castra* origin. The layout of 1100 AD within the *castra* perimeter shows little sign of the original Roman gridiron. (Morris, 1994, p.104)

2.1.2.3 <u>Rational geometry of the Renaissance</u>:

> 'The *Citta ideale* of the Renaissance is really the rationalization of a medieval type…' (Giedion, 1956, p.45).

The revival of the classical principles in the Renaissance (between the 14^{th} and 17^{th} centuries) led to the scientific interpretation of nature, in which divine expressions have been replaced by rational analysis. The Gothic period was criticised by the Renaissance scientists 'who scorned the lack of conformity of Gothic art to the standards of classical Greece and Rome' (Gardner, 1970, p.327).

In architectural terms, the Renaissance scientists renewed the classical theories of proportion based on human form. Leonardo da Vinci (1452-1519 AD) made his famous drawing of Vitruvius's '*homo quadratus*' (as shown earlier in figure 2 .6, left), and Michelangelo (1475-1564 AD) held that knowledge of the human figure was vital to a comprehension of architecture (Pearson, 2001). Leon Battista Alberti (1404-1472 AD) believed that mathematics could lay the basis for the beauty of buildings and urban spaces, and returned to the Greek mathematical system of proportions (Ching, 2007; see also Allsopp, 1959).

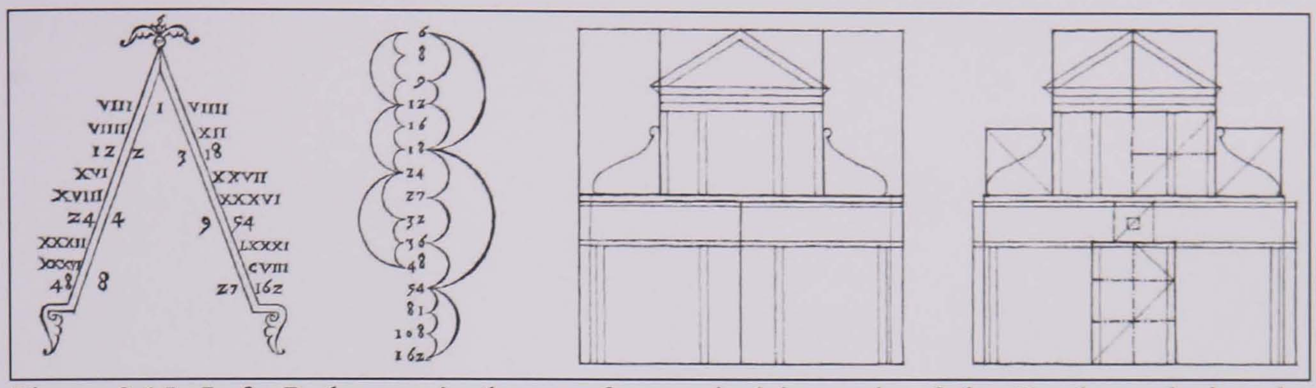

Figure 2.15: Left, Pythagoras's theory of numerical intervals of the Greek musical scale. Right, the geometrical translation of Pythagoras's theory as applied to the Renaissance façade (Santa Maria Novella) by Alberti. (Ching, 2007, p.314)

Ching (2007, p.314) writes that 'just as the Greeks conceived music to be geometry translated to sound, the Renaissance architects believed that architecture was mathematics translated into spatial units'. They applied Pythagoras's theory of means to the ratios of intervals to develop an unbroken proportion of ratios that formed the basis for the proportions of the Renaissance architecture (figure 2.15). Pearson (2001) writes that with the new 'Age of Reason' and 'the birth of modern scientific method'; architecture also came to be a science, and that each part of a building, inside and out, had to be integrated into one system of mathematical ratios.

Alberti believed that mathematics is the common ground of art and the sciences. In his books – 'On Painting' (1435) and 'On Architecture' (1452) – Alberti referred to Vitruvius and claimed that architecture is essentially to be governed by mathematical laws and proportions (see Allsopp, 1959, pp.27-45; Janson, 2001, pp.612-613). The Renaissance architects not only applied the theories of proportion and mathematical beauty to unify the interior and exterior of their designed buildings, but to integrate separate buildings and elements in an urban space. They employed Roman-origin arcades as a geometrical means to introduce order into several squares in Italian cities (Giedion, 1967).

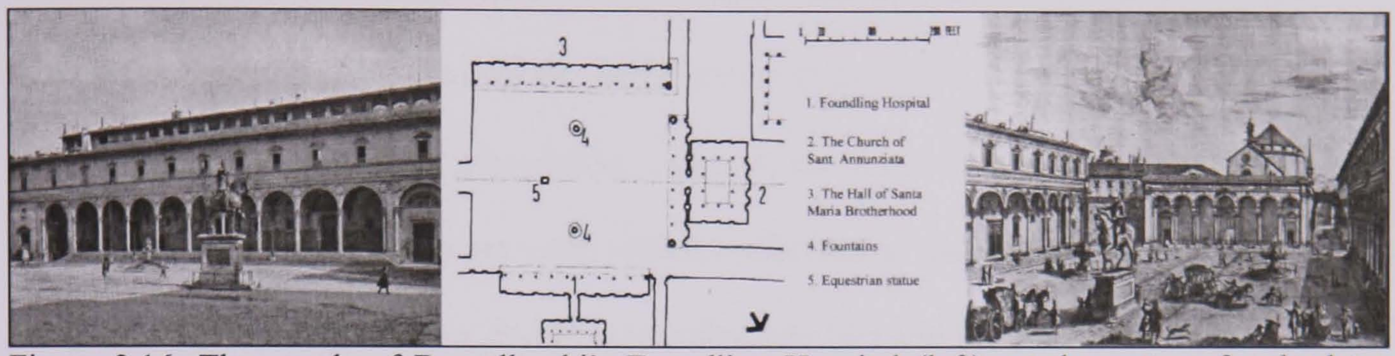

Figure 2.16: The arcade of Brunelleschi's Foundling Hospital (left) set the pattern for the later enclosure of the Piazza Annunziata (middle, and right). (Right, Allsopp, 1959, p.18; Right, Morris, 1994, p.174; Middle and left, Mumford, 1961, p.277)

According to Morris (1994), the *Pizza Annunziata* in Florence is of great significance as a work of the Renaissance urbanism; the beautiful arcaded façade of the Foundling Hospital (1417-1419 AD) – designed by Filippo Brunelleschi – initiated the pattern for the eventual enclosure of the square. The pattern was followed by some other architects such as Michelozzo in 1454 and Giovanni Caccini in 1601-1604 to apply unity to the unresolved space in front of the church (figure 2.16). The square in front of St. Peter's – first proposed by Michelangelo (1475-1564 AD) and later completed by Bernini (1598-1680 AD) – is another example of the Renaissance arcaded squares (figure 2.17).

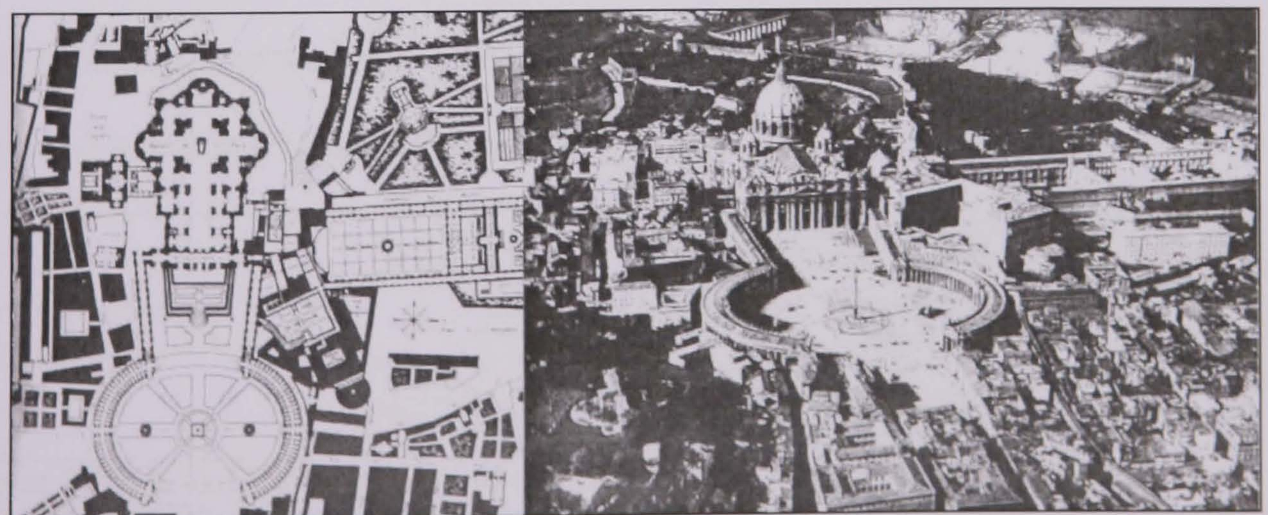

Figure 2.17: Arcades as means of imposing geometrical order on former irregular public places during the Renaissance; the plan and aerial view of St Peter's Square. (Benevolo, 1980, pp.585, 587)

Apart from the influence of the rediscovery of the Greek and Roman ideas, the discovery of perspective provided a new conception of space – focusing on the eye of the viewer – that can be interpreted by relating the world to man (figure 2.18, left). Giedion (1967, p.31) explains that, 'in linear perspective… objects are depicted upon a plan surface in conformity with the way they are seen, without reference to their absolute shapes or relations. The whole picture or design is calculated to be valid for one station or observation point only'. In a perspective representation, therefore, every element is related to the unique point of view of individual inspector (see also Lorenz, 2003; Hersey, 2000).

During the Renaissance, principles of perspective became a powerful attitude of mind in drawing, painting, architecture, and city design. In architectural terms, it meant that the space as an entity with the interactions of thousands of separate elements could be coordinated by only one or two vanishing points. Figure 2.18 shows perspective principles with one and two vanishing points in the work of two Renaissance artists, and the reconstruction of 'Filippo Brunelleschi's (*circa* 1425) attempt to create a painted optical projection of the Florence Baptistry, the Pizza San Giovanni [and Piazza della Signoria] in which it stood' (Hersey, 2000, p.162).

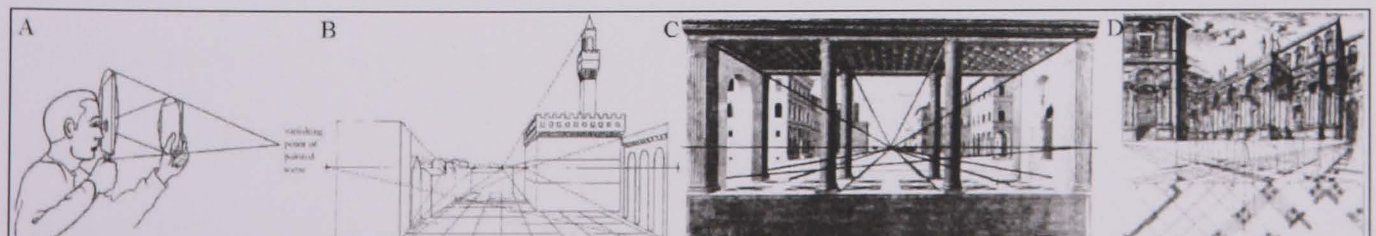

Figure 2.18: A and B) reconstruction of Brunelleschi's experiment (showing a view of Piazza della Signoria). C) An architectural scene in one-point linear perspective by an unknown artist (*circa* 1470 AD). D) two-point linear perspective by Ferdinando Galli (1711 AD). (C, Benevolo, 1980, p.523; A, B, and D, Hersey, 2000, pp.162, 163, 166)

The discovery of perspective, together with the revival of Vitruvius' ideas on good city form, inspired some of the Renaissance scientists from Antonio Filarete (1404–1472 AD) to Vincenzo Scamozzi (1552–1616 AD) to develop the theory of ideal cities, and led to the concept of radial streets and straight axes a little later in the Baroque period. According to Batty and Longley (1994, p.23), 'the need for regularity laid out city blocks, ideal town plans that were much more ambitious than anything previously'; and therefore, the Renaissance can be called 'the time of high theory for the city of pure geometry'. And, Giedion (1957, p.45) interpreted the star-like geometry of the Renaissance ideal cities as 'the rationalization of a medieval type' in which the castle, cathedral, or main square formed the core of the town and encircled by several belts of houses (figure 2.19).

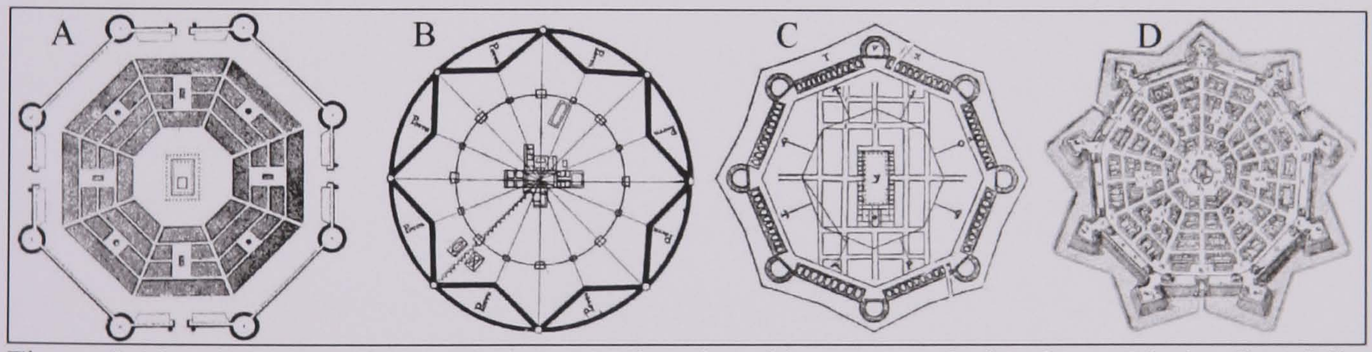

Figure 2.19: A) Geometric translation of Vitruvius' idea on good city form; B) the first fully planned ideal city by Filarete; C) the ideal city of Danieli Barbaro based on his commentary on Vitruvius; and D) Palma Nova, realised by Scamozzi. (Morris, 1994, pp.169-172)

The Renaissance town planning flourished during the Baroque period (*circa* 17^{th}-18^{th} centuries) when the city became a functional, calculated, homogenous, and comprehensive work of art that represents an object of prestige (Lorenz, 2003). Idealized planning principles were also applied to existing cities by the construction of geometrically regular fortifications, but also by cutting up the existing structure for installing radial and axial streets (figure 2.20). The star-shaped towns and the Baroque axial streets were also a logical response to the Renaissance perspective. As Giedion (1957, p.54) describes, it is based on 'a strictly limited range of distance and demands a measurable point of optical arrest' in which the horizontal lines along the straight street set a focal interest in an architectural element (e.g. an arcade, a statue, a city gate, etc) 'in the extreme background as a sort of ultimate target for the eye'. In other words, a focal interest terminates a vista.

Figure 2.20: The conformity of radial and axial streets to the Renaissance perspective. Left, plan of new streets of Rome, following the schemes of Sixtus V. Middle, the three streets that converge on the Piazza del Popolo. Right, a masterpiece of perspective in the short street of the Uffizi in Florence. (Left and middle, Benevolo, 1980, pp.582, 592; Right, Mumford, 1961, p.276)

In the 17th and 18th centuries, the Baroque style tried to enforce its principle, wherever it could, to give a uniform appearance to an existing unplanned city. Kostof (1991, p.44) writes:

> 'Baroque city-makers everywhere urged, or legislated when they could, that street defining buildings be brought to the edge of their lots in a straight line, and further, that they be given identical facades'.

After the implementation of the radial streets and straight axes in Rome under Pope Sixtus V (during the late 16th century), these principles were widely applied to other European cities such as the proposed plans for the city centre of London after the great fire in the late 17th century; the palace parks of Versailles and Karlsruhe in the 17th and

18th centuries respectively; Nash's Regent's Park in London during the early 19th century; Haussmann's Paris in the mid-19th century and so on (figure 2.21, from a to e).

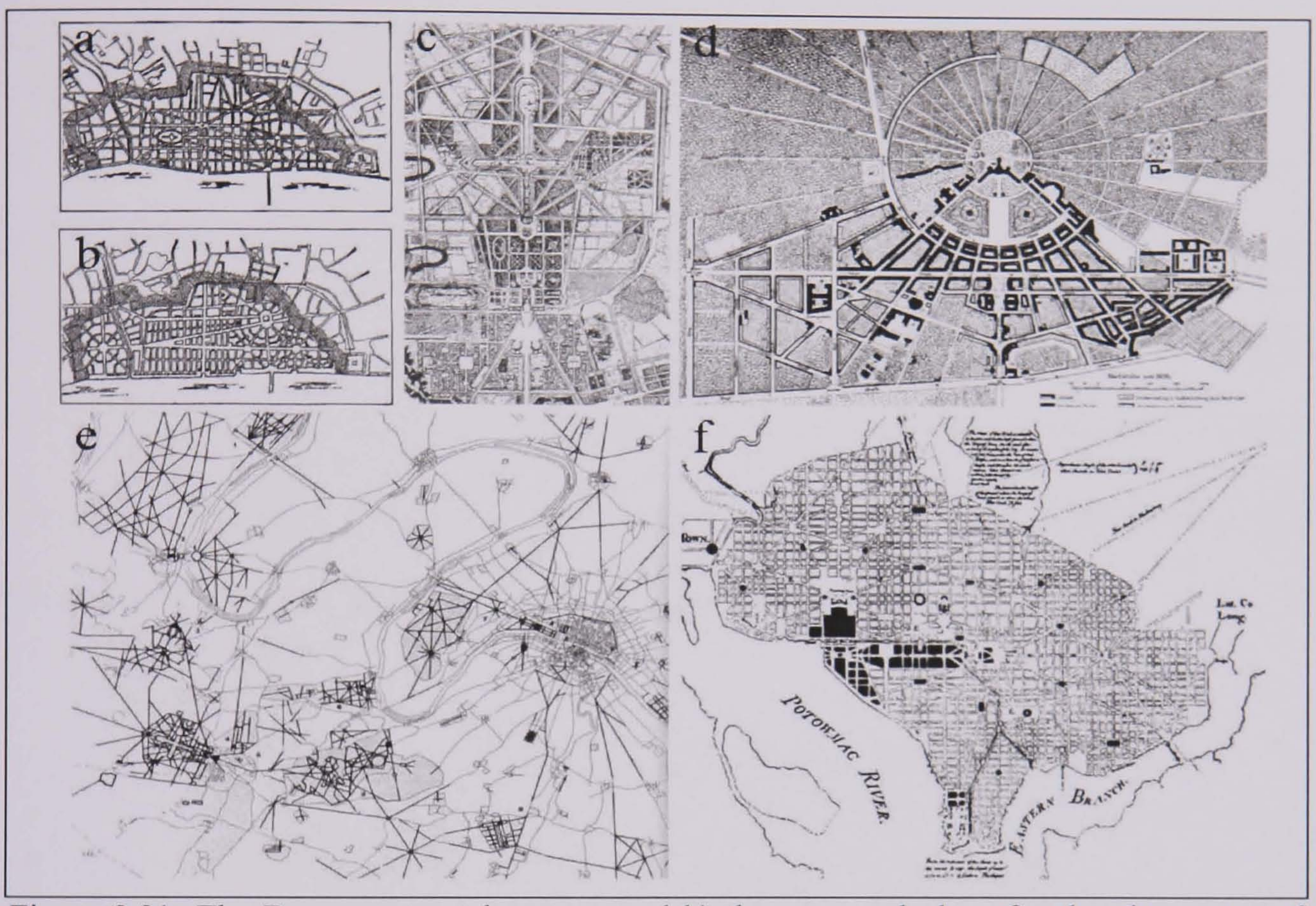

Figure 2.21: The Baroque street layout; a and b) the proposed plans for the city centre of London by Evelyn and Wren in the late 17th century, c and d) the palace park of Versailles and Karlsruhe, e) plan of the environs of Paris during the mid 18th century, and f) L'Enfant's plan of Washington DC in the early 19th century. (a, b, c, d, and e, Benevolo, 1980, pp.668-718; f, Morris, 1994, p.351)

From the late 18th century onwards, however, it was the application of the pure gridiron based plan that became popular again in the planning of many rapidly growing European and American cities – except L'Enfant's plan for Washington DC (figure 2.21, f) which was claimed to be under the influence of Baroque planning layout (Benevolo, 1980; Mumford, 1961). Batty and Longley (1994, p.22) write, 'Cities in the new world resembled those in the old until the early 19th century when rapid expansion led to widespread application of gridiron as a matter largely of speed and convenience, and perhaps through a sense of modernity – a break with the past'.

2.1.2.4 Pure geometry of modernism:

From late the 19th century, an important shift from classical geometry caused a massive change in architecture. There are indications that two core architectural movements of the 20th century – a) the overly simplistic strategy of modernists; and b) the anti-traditional scheme of deconstructionist philosophers – have separated themselves from mathematical beauty in its traditional key aspects (Salingaros, 1999). The modern movements criticized the traditional view on proportion, size, form and detail. Traditional symmetry (figure 2.22) was called intellectual laziness, ornaments were considered as an unnecessary veil hiding the real face of buildings, and proportions were defined in new ways.

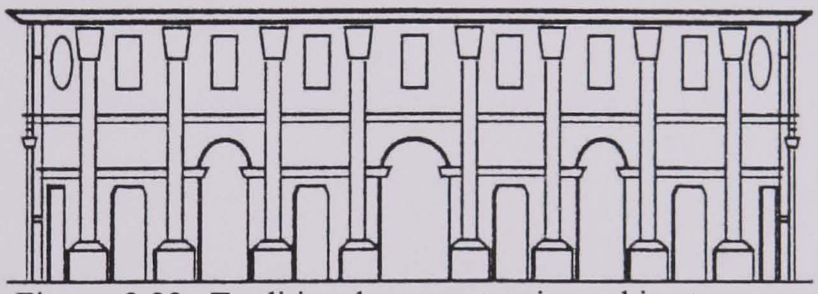

Figure 2.22: Traditional symmetry in architecture was called intellectual laziness. (Bovill, 1996, p.1)

In 1908, the Austrian architect Adolf Loos, and a little later in 1917, the Swiss architect, Charles-Edouard Jeanneret – better known as Le Corbusier – banned ornament from architecture: this became a rule followed by other modernist architects. Loos, both in his book, Ornament and Crime, and his designs (e.g. in the Steiner Haus, figure 2.23), clearly showed an aversion to ornament and found it 'obscene' – to him it was not compatible with modernity. Harries (1998, p.32-33) argues that 'Loos's argument parallels one that Enlightenment critics had formulated against the decoration-obsessed culture of the Rococo'.

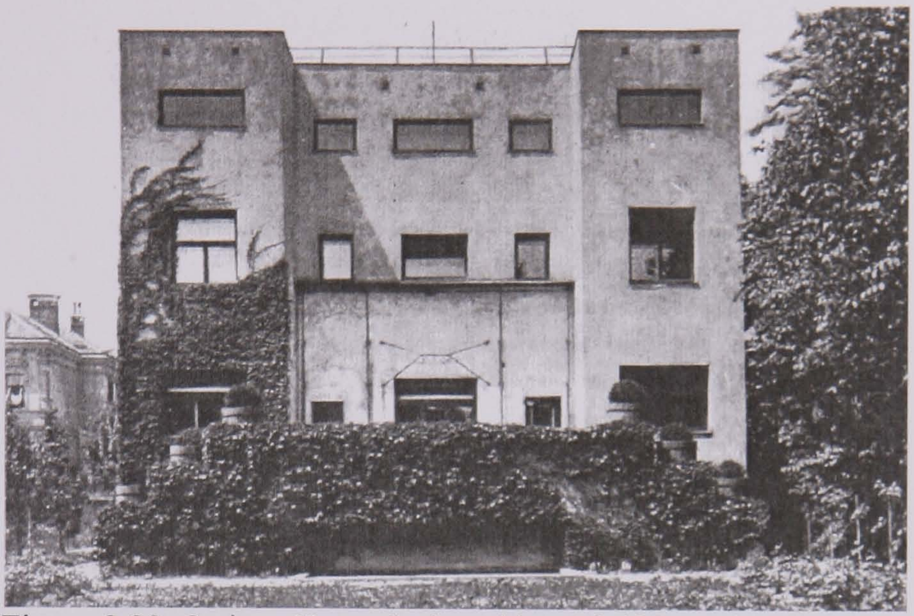

Figure 2.23: Steiner Haus, designed by Adolf Loos in 1910. The elimination of ornament in modern movement. (Harries 1998, p.41)

Modernists condemned the material culture of mankind accumulated over millennia from around the globe, and instead developed the theories of "minimalism", and "purism". They believed that form should be purified from any unnecessary elements, colour, ornament, and detailing, and therefore, form needs only to follow its purpose – "form follows function" (Baker, 1989). The modernists' belief is well described in the following quote:

> 'They claimed that machine and other man-made artefacts should respond to the same laws of economy and the selection through fitness of purpose that are apparent in nature… and nature contains truths of form following function' (Bovill, 1996, pp.136-137).

The pioneer modernists believed that scaling relationship, proportion and organizational order are to be restricted to the functionality of the space. The modulor man of Le Corbusier (figure 2.24, left), considering human scale in designing space, suggested a kind of geometrical order which could be applied to 'a vast range of scales from tables to cities'(Hersey, 2000, p.214). Le Corbusier generated a panel exercise of lattices (figure 2.24, right) to illustrate the diversity of sizes and surfaces that could be obtained with the proportions of the modulor. The proponents of his modulor idea believe that he achieved a proportional harmony by setting a system of measurements that could govern lengths, surfaces, and volumes, and maintain human scale everywhere; Ching (2007, p.319) claims that 'it ensures unity with diversity'.

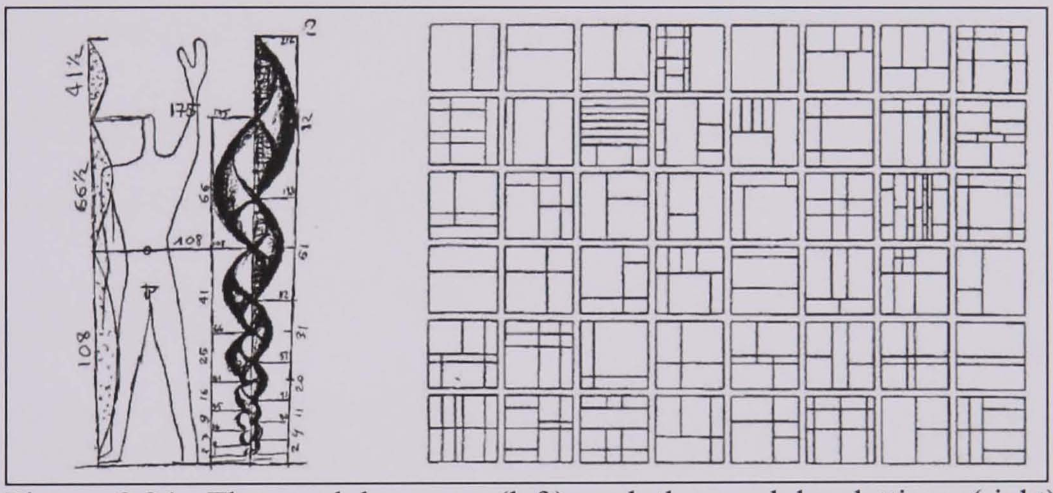

Figure 2.24: The modulor man (left) and the modulor lattices (right) generated by Le Corbusier in 1946. (Hersey, 2000, pp.212, 218)

2.1.3 Pure geometry and design quality

2.1.3.1 <u>Purism and critics</u>:

> 'Ornament and function are indistinguishable' (Alexander, 2004, p.331).

The movements after modernism criticized the notion of reductionism and purism in modern architecture. The nostalgic view of postmodernism, looking back to the form and shapes before modernism (e.g. work by Graves), the detailed structures in High Tech Style (e.g. work by Foster, Rogers), the idea of "superimposed layers" and "curved shapes" in Deconstruction Style (e.g. work by Eisenman , Hadid), all seek something missing: 'quality', or as Alexander *et al* (1979, p.28) called it, 'the quality without a name'.

The critics believe that the modulor idea of modernism – associated with purism and minimalism – was more in favour of easier, faster, stronger, and cheaper construction rather than making formal proportional and scaling relationship between the components and the structure. Salingaros (1999) argues that purism does not suggest "depth" and "richness" in design. He claims that, while the idea may seem an action of merely economic and stylistic interest, it has indirect but serious consequences: the elimination of ornament. It removes all structural differentiation from the range of scales 5mm to 2m or thereabout. He believes that the <u>lack of textural progression</u> under 2 metres makes a modern façade cold. Other critics have raised the same point in different phrases such as:

> '… that is why some modern architecture never accepted by general public. It is <u>too flat</u>' (Bovill, 1996, p.6).
>
> 'It is obvious that we immediately feel when a building is too simple, raw and <u>without depth</u>. We say it <u>lacks character</u>, or is impoverished' (Jencks, 1997, p.75).
>
> '… the lack of interest in formal composition in modern architecture is one of the causes of its <u>lack of scaling features</u>' (Crompton, 2002, p.459).

Alexander (2002, 2004) also raises a similar point and provides a comparative example. He criticises the minimalistic concept and the modulor proportion in Le Corbusier's Marseilles block apartments (figure 2.25, right) as compared to the hierarchy of scale in tile-work at a Mosque (figure 2.25, left), and states that it lacks some essential '<u>levels of scale</u>' (Alexander, 2002a, 149). He believes that a good design tends to have fine details at its different scales termed 'levels of scale'. He defines the term as: 'a beautiful range of sizes exist at a series of well-marked levels, with definite jumps between them' (Alexander, 2002a, p.145). In other words, there should be a proportional relationship between constituents of a space or a piece of architectural design, linking each level of its hierarchical structure to the next level and to the whole.

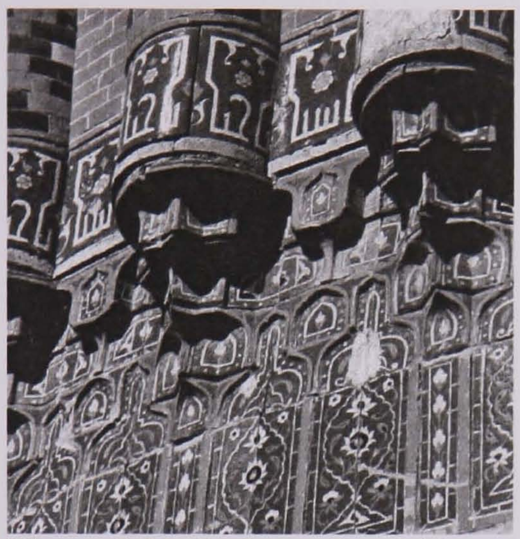

Figure 2.25: Left, profound hierarchy of scale in tile work at a mosque in Meshed, Iran. Right, poorly developed levels of scale in Le Corbusier's Marseilles block of apartments. (Alexander, 2002a, p.149)

2.1.3.2 <u>Scaling relationships and fractal concepts</u>:

The brief historical review reveals that designers have long sought the 'scaling relationship' between the whole and the constituent parts of a complex form to find an arithmetical and geometrical basis for what was thought to be good design. This notion can also be traced in theories of complexity and fractal geometry, which will be defined and elaborated in the next two chapters. However, in the first instance, it is helpful to imply how simply these seemingly difficult terms might be understood just by interpreting the Ruskin's thought of good design:

> 'all good ornaments and all good architecture are capable of being put into shorthand; that is, each has a perfect system of parts, principal and subordinate, of with, even when the complemental detail vanish in distance, the system and anatomy remains visible' (Ruskin, 1904, vol.3, p.208).

Crompton (2002) and Unrau (1978) argue that Ruskin's belief about good ornaments and good architecture can be interpreted as a fractal concept. 'In short, ornament ought to reveal new details and forms as one gets close. Of course a fractal is well adapted to do just that; indeed in their most developed form, fractals look the same from whatever distance they are viewed' (Crompton, 2002, p.456).

The notion of 'lack of scaling features' – raised by some critics – echoes the similar advice given by Ruskin (1904) about producing composition with scaling rules. Whether it is an ornament, a building or an urban space, Ruskin (1904) stated that:

> 'An ornament should be designed so that it is meaningful when seen at long, intermediate, and close range' (quoted in Crompton, 2002, p.456).

Having this quote of Ruskin, Crompton (2002, p.456) believes that Ruskin's argument is well expressed by his dislike of the decoration on Constitution Arch in London (figure 2.26), 'where there is a big jump in scale between a patch of intricate cast-iron decoration and the mass of smooth stone in which it is set'.

Figure 2.26: Constitution Arch in Hyde Park, London, designed by Decimus Burton in 1828. The lack of intermediate scale causes a big scale jump between a patch of intricate cast-iron decoration and the mass of smooth stone. (Quoted from Crompton, 2002, p.456; the photo taken by the author, June 2008)

This view is also emphasized by Cooper (2000, p.177), who writes that '… in order to maximise visual interest a building should have a "cascade" of detail that is revealed in greater and greater distinction as the viewer approaches', which is exactly what Alexander (2002a) means by "levels of scale", and Bovill (1996) means by "the progression of texture". Figure 2.27 shows one of wonderfully diverse residential projects designed by Lucien Kroll incorporating the progression of texture.

Figure 2.27: Three levels of scale at a residential project designed by Lucien Kroll. It shows the progression of texture revealed as the viewer approaches the façade. (Bovill, 1996, p.186)

Bovill (1996, p.5) suggests that 'Architectural composition is concerned with the progression of interesting forms from the distant view of the façade to the intimate details. This progression is necessary to maintain interest. As one approaches and enters a building, there should always be another smaller-scale, interesting detail that expresses the overall intent of the composition'. As experts in fractal theory suggest, this is 'the fractal concept', which is the formal study of this progression of self-similar detail from large to small scales.

2.2 Part Two: The Failures of Conventional Geometry

Part one of this chapter highlighted some of the key achievements in the science of geometry through the history of architecture and urban form and its impact on shaping the built environment. Despite the conceptual diversity between the styles at different historical periods, it can be claimed they have been all developed under dominance of one common influential concept: "the Euclidean geometry of straight lines". The principles of the conventional geometry of Euclid have been used whenever human have attempted to regulate and order the built environment. As exemplified in part one, the geometry of straight lines in general, and the gridiron layout in particular, have been largely applied to all types of the cities that can be termed "planned", but not to those which are named "unplanned" or "organic". In urban terms, Euclidean geometry can be argued to have the following advantages and disadvantages:

1. While Euclidean grammar can describe the relationship between the constituent parts of a planned urban context, it fails to explain the irregularity existing in a city or parts of a city grown organically without a predetermined plan.
2. While Euclidean geometry can impose order to an existing organic urban context, simultaneously, it creates thousands of mistakes!

The second part of this chapter will elaborate the above argument by comparing the main differences between the geometry of planned and organic cities. This contributes to the main goal of this chapter to establish some reasons why new approaches towards city forms and shapes are essential in the light of the theories of complexity and fractal geometry.

2.2.1 The strengths and weaknesses of Euclidean geometry in interpreting planned and organic city form

> 'Man walks in straight line because he has a goal and knows where he is going' (Le Corbusier, 1924, quoted by Kostof, 1991, p.95).

For years and years, the idea of a planned city with pure geometry was believed to be an ultimate utopia for a city, and therefore, the planning goal was to reduce irregularity to achieve more order (Batty and Longley, 1994). At its purest, a planned layout would be a grid, or else a centrally planned scheme like a circle or a polygon with radial streets which are issued from the centre; however as Kostof (1991, p43) claimed 'the grid is by far the most common pattern for planned cities in history'. Le Corbusier (1924) believed that the reason for wide applicability of the grid in the history is that its planning is often simple and pragmatic, and so he claimed that the concept could be still valid in designing of the modern cities. He claims that no better urban solution recommends itself as a standard scheme for disparate sites to create order.

Further to some successes that the geometry of straight lines has achieved through the history of urban forms (as discussed in part one), Kostof (1991, pp.95-157) claims that the grid, in particular, has served human needs through the following purposes:

- Practical purposes (e.g. it facilitates movement in working areas in city both for pedestrian and vehicle)
- Political purposes (e.g. it has been employed to control both internal and external treats)

- Economical purposes (e.g. it serves well the need for fast development when time and money are in shortage)
- Social purposes (e.g. a means for the equal distribution of land or the easy parcelling and selling of real estate)
- Finally, it is claimed to be an exceedingly flexible and diverse system of planning; the orthogonal street pattern of grid systems makes parallel street lines, which are not immutable. The system can curve around irregularities on the ground without betraying its basic logic.

It is true that the science of geometry in general and the gridiron in particular have had some successes through the history and served human needs, but perhaps it is also true to claim that the geometry of Euclid as applied to city forms has always associated with the conventional thought of reductionism and simplicity. However, as Batty and Longley (1994, p.2) argued, 'planned cities are cast in the geometry of Euclid but by far the majority, those which are unplanned or planned less, show no such simplicity of form'. This brings up some immediate questions:

1- Can Euclidean geometry explore the forms beyond a planned city and explain the spatial relationship between the constituent elements or morphological features within an organic city?
2- Even planned cities experience evolution and change; are Euclidean principles still valid and capable of interpreting urban forms after they have been changed?
3- While the shape of a planned city is usually determined only in two (horizontal) dimensions, can Euclidean geometry analyse the third (vertical) dimension of urban forms in its city panorama?

Clearly, the answer to the first two questions would be negative. The majority of cities display a mixture of both types – planned and unplanned – which their form would not be seen as being regular and purely geometric; thus, it cannot be analysed by Euclidean grammar. Furthermore, the regularity in planned cities is not usually consistent. Cities may sometimes start with sustained regular plans, but more commonly, their form involves continuous unpredictable processes of evolution over the time (Marshall, 2009). It can be claimed that 'no two planned cities are exactly alike' (Kostof, 1991). As Batty and Longley (1994, p.2) explain, the reason is that 'even planned cities are adapted to their context in more natural ways once the plans come to be implemented'. Since the forces that engender it are many, the new form does not display the clean lines and continuity of the original, and thus, it is not explicable in every detail by Euclidean geometry any longer.

Figure 2.28: Geometrical evolution in ground plan of Baghdad during the 8th and 9th centuries. (Kostof, 1991, p.13)

An example of such changes can be seen in the famous round city of Baghdad by Caliph al-Mansur in 8th century (figure 2.28). It hardly ever existed more than a century in the perfect shape conceived for it (Kostof, 1991). Another obvious example can be observed in some Roman cities. As figure 2.29 illustrates, the initial regular Roman form was evolved vividly towards the Middle Ages period in a way that the latter form offers the merest similarity to the original layout (see also the examples shown earlier in figures 2.13 and 2.14).

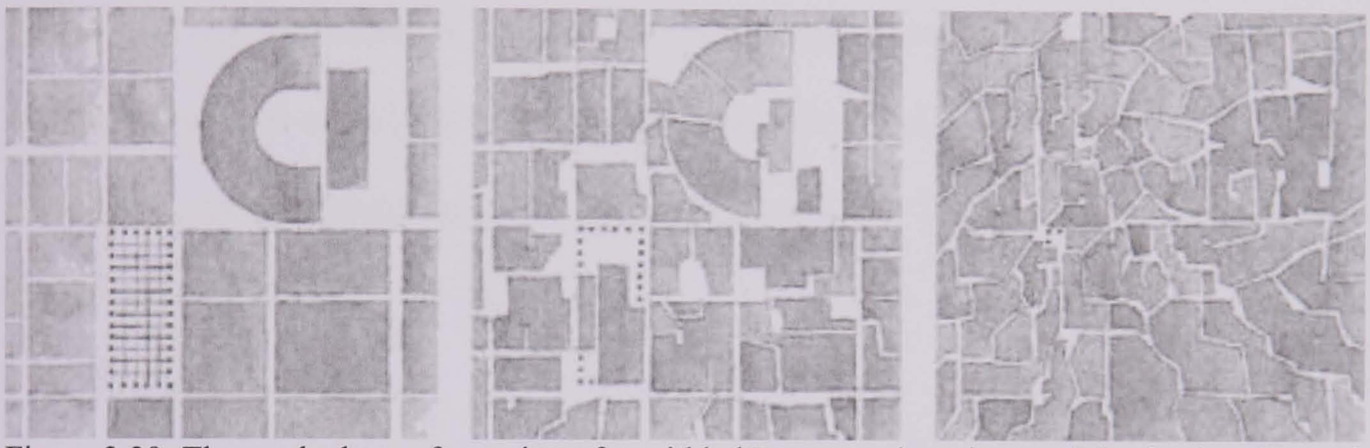

Figure 2.29: The gradual transformation of a gridded Roman colony into an Islamic city. (Kostof, 1991, p.49)

The answer to the third question would also be negative because the spatial pattern of elements composing a planned city in terms of its networks, buildings, and spaces are defined through its geometry mainly, but not exclusively, in two rather than three dimensions. While the shape of a planned city is determined in two dimensions at somewhat large city scales, its third dimension is usually formed from many individual decisions at much smaller scales (architecture or urban design level). In this sense, streets that can be read as straight and uniform on the city plan might be seen irregular in their elevation. Even where some restrictions are applied to an urban facade by planning policies, the buildings' height and their facades are usually the product of a negotiated ever-changing design between individual owners and the planning authority.

Although there are also places, where urban designers attempted to apply order to the third dimension (e.g. identical facades during Baroque), these are usually limited to the small city scales such as a square or a street and might be seen less regular if observed at larger scales. Nonetheless, it can be claimed that, in most cases, the cities were only planned in two (horizontal) dimensions. Kostof (1991, p.44) stated that 'the regularity of the planned city is conditional.... even when buildings are marshalled like troops along straight lines of an urban grid, the degree of animation in their mass and, more essentially, variable height can result in picturesque formations believed to be congenital to the unplanned city'.

Therefore, in any case, the extent to which city-form is ordered or planned is always a matter of degree. In this sense then, all cities show some irregularity in most of their parts, which are not explicable by Euclidian geometry. Instead, as Batty and Longley (1994) suggest, they are all ideal candidate for the application of fractal geometry.

2.2.2 The association of mistakes with the application of Euclidean geometry

It was discussed that the ultimate goal of designers in creating order where a city exhibits irregularity, came to be realised by the wide application of Euclidean geometry. In his recent essays on "The Nature of Order", Alexander (2002b, 2004) raises a very important point stating why the application of the conventional geometry as applied in planned cities creates 'mistakes'. The main reason has to be sought in the contrast between the geometry of planned and unplanned settlements, and hence, lies in the intrinsic incapability of Euclidean geometry of straight lines to adapt the existing environmental factors when a city or a part of a city is planned "all at once".

In a planned settlement, the physical variables (length, area, volume, angle, etc) are usually fixed by rigid straight lines imposed on every dimension. They are designed at once or in a very short period by one person or by a design team. Inevitably, such a design process and its output are deterministic. This means physical elements such as lines, edges, and positions are strictly determined by planners and designers on their drawing boards and as Alexander (2004) explained, the result is fabricated.

By contrast, in an organic structure, its plan is generated over a history extended in time, which is not made by central decision of an authority. It is evolved gradually by decisions made by individual people (Kostof, 1991). Each existing line, surface, and space is refined based on changes in the occupiers' needs and through step-by-step adaptation according to socio-economic factors and the environmental conditions of the place, and the house such as topography, climate, etc. Therefore, the main differentiation between planned and organic city forms lies in the process creating them. The vast superiority of the geometry of organically generated plans as Alexander (2002b, p.86) noted is that it avoid mistakes; He claims that, 'in all fabricated plans, the overwhelming majority of possible mistakes are actually committed', but how?

Each element of an object represents a decision. At architectural scale, decisions should be made about part, line, edge, position, colour, size, etc. At urban scale, decisions are about streets, house groups, courtyards, party walls, paths, blocks, etc. Furthermore, if we accept that each line has created space on either side of an element (in and out), and each represents four or five possible decisions about space (through size, convexity, adjacency, organization, etc), then it can be claimed that each decision as applied to each line has the possibility of being wrong. It means that the element as placed, sized, and oriented, may be well adapted to its neighbours, to the space around it, to the conditions, which exist, and to the conditions arising from the structure of surrounding elements – or it may be badly adapted to the neighbours, conditions, spaces, arising from surrounding elements.

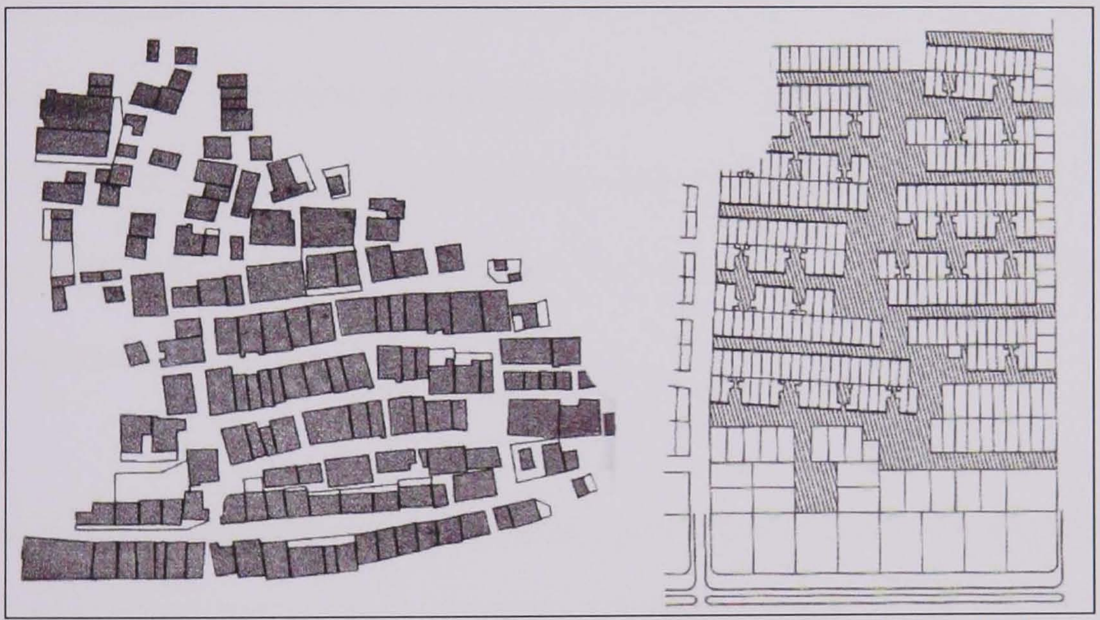

Figure 2.30: Left, a generated organic structure, Shilnath, India. Right, a fabricated planned structure designed by B. V. Doshi, Vatsu Shilpa. (Alexander, 2002b, pp.182, 184)

Providing an example of an organic plan (Shilnath, figure 2.30, left) and an example of fabricated plan (Vastu Shilpa, figure 2.30, right), Alexander (2002b) argued that, in a plan like that proposed for Vastu Shilpa which is composed of 400 hundred houses, hence about 1600 line/elements, and as each line is associated with five decisions, the total number of decisions that must have been made, can be roughly estimated as:

$$5 \times 1600 = 8000$$

In the proposed plan of Vastu Shilpa (in two dimensions), more than 8,000 possible decisions have been made; however, many more decisions should be made to determine the third dimension of the city. Each of these decisions was associated with potential mistakes in a deterministic planned scheme, and by that Alexander (2002b, p.187) means that:

> 'the line was drawn on a drawing board, without any opportunity for the line to be modified, or adjusted, according to realistic perception of actual difficulties and opportunities on the place itself.... in a professional planning/design/development process, this failure of adaptation is inevitable, and that at the time of its creation no process was put in place to remove these mistakes.'

By contrast, in Shilnath, each line represents a decision that was put down by people once at a time over a history extended in time. Because of this relatively slow decentralised process of decision-making associated with the needs of the situation each of five possible mistakes that existed in Vastu Shilpa, is here corrected, by adaptation and careful adjustment of each line.

In general, an organic structure emerges out of a generating process. The generating process – through iterated, repeated, sequence of transformations – makes it progressively 'more and more profound, more and more living' (Alexander, 2004, p.95). This creates a quality that is the result of self-generating process, which causes a complex city form, becomes eventually something more than sum of its components. As Alexander (2002b, pp.182-201) suggests, this is the quality of "deep complexity", and according to Batty and Longley (1994), the geometry that represents such complexity can not be Euclidean: it must be fractal.

In short, the compositions and the plans that designers propose at once for a city or part of a city, inevitably, do not have such quality. It is impossible to generate a complex form at once by simply adding its components together. Euclidean geometry is only capable of creating linear relationships between the components of a design, which the resultant form cannot be called deeply complex. As they are planned through a rather short process of design, they never reach a high level of complexity. Finally, there is always a risk of removing the complexity at anytime when an urban intervention imposes its pure geometry of Euclidean forms on an existing organic city context. That is why complexity theorists advise that urban interventions are to be avoided at large urban scales (Marshall, 2009) and are to be carried out with extreme caution even at a small city scales (Batty, 2008).

2.3 Chapter Summary

This chapter began with pointing out the significance of the mathematical and geometrical approach in studying architecture and urban forms. The literature was reviewed to highlight some of the key achievements of the science of geometry at different historical periods and its impact on the way human shaped his built environment. The conventional geometry of straight lines – known as Euclidean geometry – was shown to be the main and powerful tool in the hand of planners and designers at any time they attempted to apply order to city forms. However, the credibility of this geometry in analyzing the way a city changes and evolves was called into question.

Some of the failures of the conventional geometry of Euclid were discussed to establish the reasons why a new realistic insight into urban morphology is required in the light of the theories of complexity, and fractal geometry. However, before asking how these new theories may be applied to city forms, the questions that remain to be answered are: What are the definitions for the terms "complexity" and "fractal"? What is the relationship between these terms? Moreover, can Euclidean geometry be replaced by fractal geometry in designing objects from small architectural elements to large city forms and shapes?

The research seeks to find some answers to above questions in the following chapters. In chapter three, the origins and definitions of the terms fractal and complexity will be explored through the recent literature. It also will be discussed that, even though cities are man-made, but dissimilar to other artefacts, they are better understood in terms of nonlinear and living self-organized systems rather than conventional linear and mechanical approaches.

CHAPTER THREE

COMPLEXITY, CHAOS, AND FRACTAL GEOMETRY: THE THEORETICAL BACKGROUND

Introduction

In the previous chapter, it was argued that the conventional geometry of Euclid fails to describe many real physical and functional aspects within cities – particularly those aspects characterized as organic change. Recent developments in complexity, chaos, and fractal theories have opened new windows for the researchers studying complex systems, both in their form and in function. These researchers claim that cities are to be considered as complex systems demonstrating chaotic behaviour in their subsystems; and, hence, the pattern or the geometry which emerges out of such chaotic behaviour is fractal not Euclidian. In order to examine the credibility of this claim and to verify how a city can be observed as a self-organizing complex system, the principles underlying chaos and fractal theories and the way they are related to the science of complexity will be discussed in this chapter.

The chapter comprises three main parts. The first part explores the terms, the origin, and the main parameters by which the concept behind chaos theory can be defined. In the second part, complexity theory and its relationship with chaos theory are discussed; then, the literature will be reviewed to investigate the properties and characteristics of complex living systems. This review is essential to show why cities are to be viewed, studied, and treated as self-organizing complex systems. The third part of the chapter will focus on the geometry of complexity – fractals. Some examples of fractal phenomena will be discussed to explore the notion of non-integer fractal dimension as opposed to integer Euclidean dimension. Finally, among the methods of measuring fractal dimension, those which will be employed at the empirical stage of this research will be explained in more detail.

3.1 Part One: Chaos Theory; Literature Review

3.1.1 Understanding of chaos and complex systems

The science of chaotic complex systems is relatively new, particularly as applied to urban systems. It is, therefore, necessary to begin with an understanding of what it means in theory. "Chaos" is one of the key terms in studying complex systems. Some classic publications frequently used the term "edge of chaos" to refer the tendency of complex systems to self-organize to a state roughly midway between globally static (unchanging) and chaotic (random) states. However, the term "chaos" has become unpopular with many mathematicians and scientists who, instead, find the word "dynamics" to be more appropriate to their own particular part of academia (Byrne, 1998). Nonetheless, this chapter refers to the term "chaos" firstly because it is a key word in the work of the pioneer scholars who developed later the notion of complexity, and secondly because it is more relevant to the notion of complexity and has a wider implication than the term "dynamics."

Experts in chaos and complexity theories precisely reject 'reductionism and the validity of analytical strategies in which things are reducible to the sum of their parts' (Byrne, 1998, p.14). Price (1997), however, claims that these theories are neither "reductionism" nor "holism" in the conventional sense of the words. 'Holism typically overlooks the interactions and organization, whereas complexity theory pays attention to them' (Price, 1997, p.10). Complex system theorists have defined it as a science dealing with living structure with emergent properties (Wallczek, 2000). This means that the complex system is not created merely by interaction of densely coupled systems, or by some magic probabilistic occurrence, but comes into being through the self-organized nature of its own living structure (Batty, 2005; and Alexander, 2004).

An important aspect of chaos and complexity is "nonlinearity". This refers to changes that do not occur in a linear fashion in living systems. These systems are not characterisable by linear or first-order equations, but by any variety of complex, reciprocal relationships, or feedback loops. As Byrne (1998) states, in nonlinearity, small changes in causal elements over time do not necessarily produce small changes in other particular aspects of the system, or in the characteristics of the system as a whole. Either or both may change in ways which do not involve just one possible outcome.

A further significant aspect of chaos and complexity – as opposed to mechanical models – is "time irreversibility". In reality, the crucial dimension along which change occurs is 'time'. This means that we are dealing with processes, which are fundamentally historical (Byrne, 1998). They are not time reversible. Therefore, complexity theory involves an explicit rejection of the Newtonian concept in which time is reversible (see also Kauffman, 1993; and Philips, 1994). That is why some scientists replace the clock – as the iconic symbol of the modern – with the heat engine leading to thermodynamics (Prigogine *et al*, 1984).

Jencks (1997) summarized the history of complexity in figure 3.1 and wrote that, in the 19th century, the new sciences of thermodynamics and ecology introduced directionality and holism into the equations. 'Between 1900 and 1927, quantum and relativity theories overturned determinism. In the late 1940s general system theory, plus a series of life sciences and computer sciences started to grow, and by late 1970s, the trickle become a flood, yielding a new consistent paradigm. Continuing the Post-Modern perceptions of cosmos, chaos theory, fractals… have arrived on the scene. All this can be generally conceived as the sciences of complexity, or nonlinear dynamics, or self-organizing systems' (Jencks, 1997, p.124).

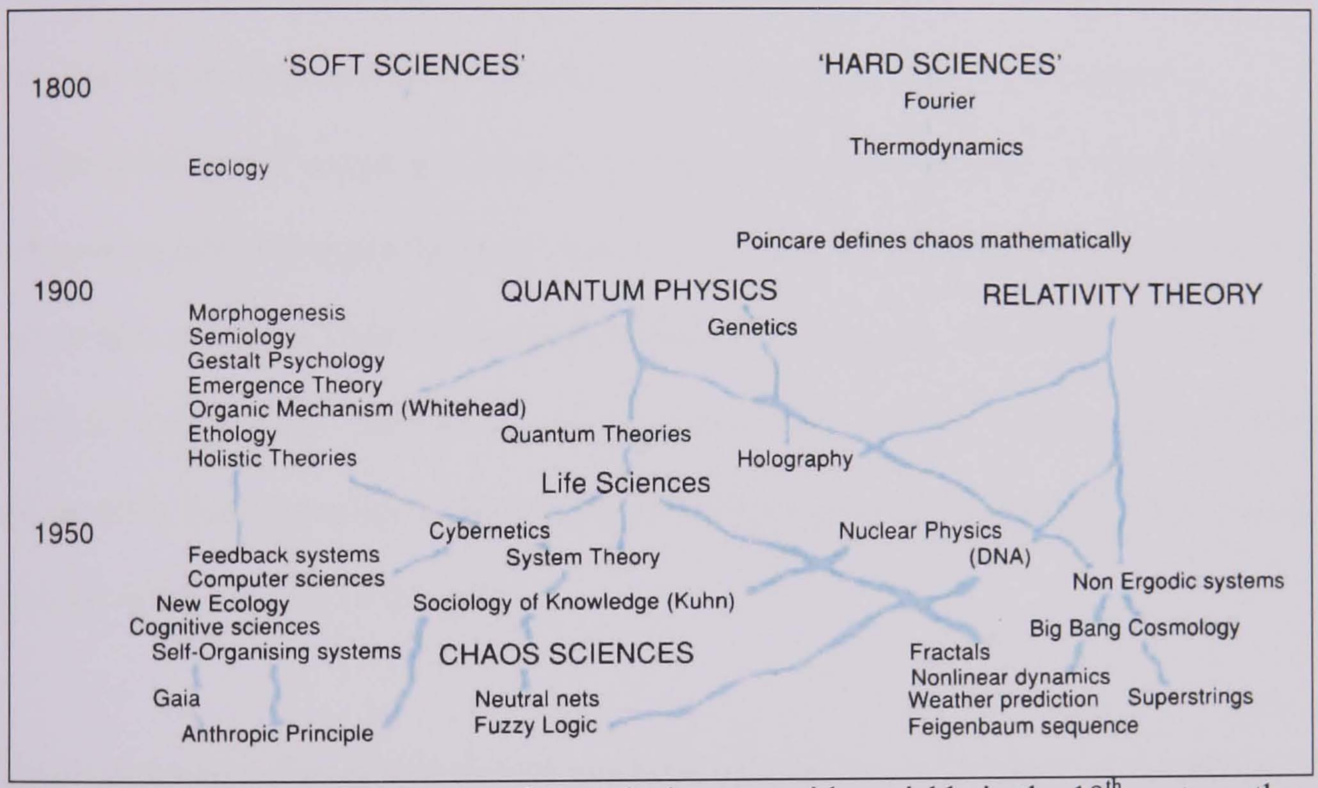

Figure 3.1: Post-Modern Sciences of Complexity start with a trickle in the 19th century, then become an interconnected river delta by the end of 20th century, with nonlinear dynamics and chaos theory. (Jencks, 1997, p.124; "Neutral nets" in this figure is incorrect, and "Neural nets" would be more appropriate)

Although the concepts of chaos and complex systems are relatively new – less than half a century old – they should be understood with a review of modern scientific developments in physics, and as most literature suggests, from a little earlier than the discovery of linear mechanics and thermodynamics – the scientific revolution of the 17th century. This review has adopted the three steps that Gribbin (2004) claims to be essential for understanding of chaos\complexity theories: "order out of chaos", "chaos out of order" and "at the edge of chaos". However, this discussion will also be broadened to other available papers written on complexity where further explanations are required. The three steps are elaborated as follows:

3.1.1.1 Step I: Order out of chaos (Linear Dynamics)

The conventional definition for 'chaos' based on what people use and as given in dictionaries is a state of complete disorder and confusion, which is a quite different way from the way in which the term is used by scientists today. 'Before the scientific revolution of the 17th century, the world seemed to be ruled by chaos… in the same way that most people still apply the word' (Gribbin, 2000, p.5). There was no suggestion that there might be simple, orderly laws underpinning the confusion of the world. Gribbin (2000, p.5) argued that 'the nearest anyone came to offer a reason for behaviour of wind and weather, the occurrence of famines or the orbit of the planets, was that 'they resulted from the whim of God, or the gods'.

Following the attempts of scientists in the early Renaissance to produce mathematical approaches for understanding underlying order in the nature, new models for the universe were developed. Galileo (1564-1642) followed the sun-centred Copernican model at a time when the theological belief of the Catholic church of 16th century could not accept it. He also developed the notions of 'motion' and 'acceleration' in a scientific way, which led to the greatest discovery of the 17th century: Newtonian universal laws of motion and gravitation. Gribbin (2000) has interpreted this progress as a new way of scientific understanding of 'order', born out of the notion of 'chaos' which was already believed to rule the universe.

Newton (1642-1727) developed a new branch of physics, called "Linear Dynamics", that deals with the effects of energy and forces on the motion of physical objects in a Euclidean space. He believed that nature could be described as a closed causal system of 'matter in motion' and governed by deterministic equations of motion. To the Newtonian view, perfect foresight based on predictability of dynamic systems is possible, if the necessary data and proper specifications of such systems are available.

Referring to the principles of the Newtonian view, Laplace (1749 - 1827) believed that all phenomena within the universe would follow the rules of mechanics. He claimed that given the Newtonian laws of motion, the initial conditions of the universe and enough time to perform the computations based on linear cause and effect relationships, he could predict the future of the universe. This view was thought to be applicable to all macroscopic systems in the nature; and, up to the early 20th century, scientists thought that they were dealing with an unchanging set of laws' (Jencks, 1997, p.124).

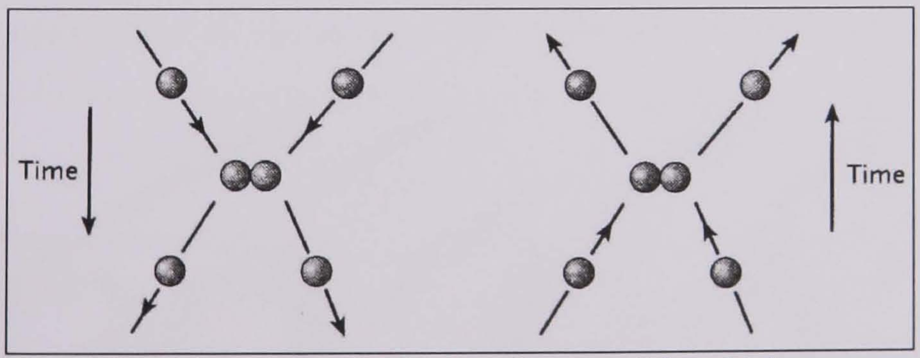

Figure 3.2: The picture looks equally plausible whichever way we draw the arrow of time. (Gribbin, 2000, p.18)

One of the key principles in the Newtonian universe is that the direction of time did not matter; equations worked just as well backwards as forwards. It means that time is "reversible" without violating the laws of motion, or in other words, Newton's laws are independent of the "arrow of time" (figure 3.2). Accordingly, this makes precise prediction possible. However, one after another, modern sciences started to challenge this static picture of the universe. Among them, the second law of thermodynamics is the first, which started the challenge showing that such a precise prediction is not possible in many real systems.

3.1.1.2 Step II: Chaos out of order (Thermodynamics)

The second law of thermodynamics was, in fact, bad news for those who believed firmly in absolute order. 'Everything tends toward disorder. Any process that converts energy from one to another loses some as heat. Perfect efficiency is impossible and 'the universe is a one-way street' (Gleick, 1987, p.308). This inefficiency was called "*Entropy*" (for definition see appendix A). The second law of thermodynamics revealed that the phenomena such as gas in a balloon, liquid cooling in a container or wood burning in a stove moved from states of low to states of high entropy and were said to be irreversible. Thermodynamics seemed to point to an 'arrow of time' (irreversibility), contrary to classical mechanics, where all phenomena had been considered reversible in time.

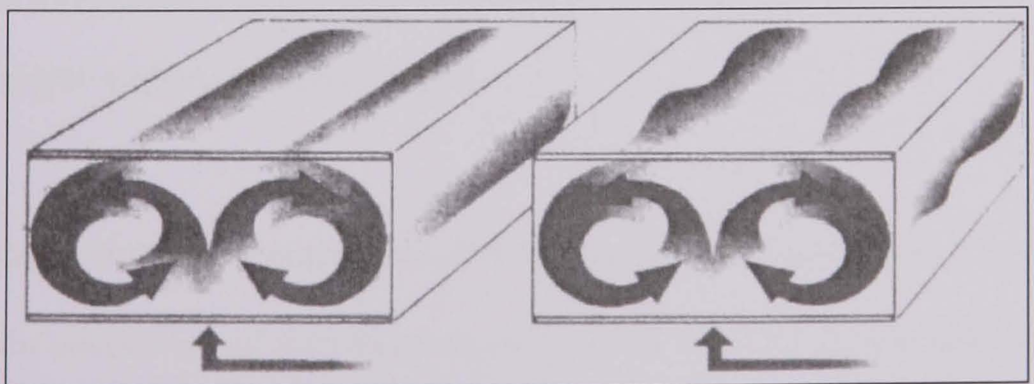

Figure 3.3: the picture shows an open system model shifting from an equilibrium state to a non-equilibrium one. (Gleick, 1987, p.25)

Figure 3.3 illustrates a simple example of increasing entropy in an open system in which, if a liquid or gas is heated, the fluid tends to organize itself into cylindrical rolls (figure

3.3, left). Hot fluid rises on one side, loses heat, and descends on the other side (the process of convection). However, when the heat is turned up further (figure 3.3, right), 'an instability sets in, and the rolls develop a wobble that moves back and forth along the length of the cylinders; at even higher temperatures, the flow becomes wild and turbulent' (Gleick p.25). The above example is a model of what happens in a real open system such as a weather system. Exchanging energy can increase entropy and turn a equilibrium state to a non-equilibrium one. The entropy is multiplied as the process continued until it reaches the stage of strange and unpredictable behaviour which Gribbin (2004) interpreted it as *'the return of chaos'*.

In the light of all this, thermodynamics, and in particular the idea of increasing entropy, became statistical ideas; in the real world, given the number of particles involved, it is overwhelmingly probable for entropy to rise but it is also possible to fall. This was not something that all physicists found easy to live with at first. Two centuries after Newton and only seventy-five years after Laplace, they were being told that the world is not deterministic in the simplest sense after all, and that chance and probability must be taken into account when trying to describe, or calculate, the behaviour of many microscopic and macroscopic systems (Gribbin, 2004).

The mechanistic worldview indeed ended at the beginning of the 20th century. If the entropy in the second law of thermodynamics was bad news for Newtonian physics, relativity and quantum theories completely changed the Newtonian view of absolute space/time. As Ho (1997, pp.44-45) states:

> 'Einstein's relativity theory broke up Newton's universe of absolute space and time into a multitude of space-time frames each tied to a particular observer, who

> therefore, not only has a different clock, but also a different map.... Quantum theory demanded that we stop seeing things as separate solid objects with definite (simple) locations in space and time. Instead, they are delocalized, indefinite, mutually entangled entities that evolve like organisms'.

The profound implications of this decisive break were recognized by some intellectual philosophers of the early 20th century such as Henri Bergson in 1916, and the English mathematician Alfred North Whitehead in 1925 (Ho, 1997). Between them, they articulated a philosophy based on organics in place of mechanics. In table 3.1, Ho (1997) summarizes some of the major contrasts between this new philosophy of organic universe organisms and the Newtonian mechanical universe.

Mechanical Universe	**Organic Universe**
Static, Deterministic, fabricated*	Dynamic, Evolving, generated*
Separate, absolute time, universal for observer (process)-dependent observers space-time frames	absolute space and space-time inseparable, contingent
Insert objects with simple locations in space and time	Delocalized organisms with mutually entangled space-times
Linear, homogenous space and time	Nonlinear, heterogeneous, multi-dimensional space-times
Local causation	Non-local causation [local-global interaction]
Given, non-participatory and hence, impotent observer	Creative, participatory; entanglement of observer and observed

Table 3.1: The table compares the properties of a system in the organic universe with a system in the mechanical universe. (Ho, 1997, p.45; the property asterisked was added by the author)

3.1.1.3 Step III: At the edge of chaos (Nonlinear dynamics)

During the mid 20th century, there were wide-ranging attempts to uncover the statistical regularities hidden in processes of natural systems that otherwise appear random, such as turbulence in fluids, weather patterns, population fluctuation, etc. These systems – later termed *"nonlinear systems"* – manifest that, they are seemingly obeying Newtonian laws of motions and gravity in principle, but can behave in a chaotic and unpredictable fashion in practice.

Most literature relating to chaotic system (e.g. Gleick, 1987; Blackwell, 1989) attributes its first discovery to a meteorologist, Edward Lorenz, who recognized strange patterns while working on his model for a weather system. In the early 1960s, Lorenz was seeking an accurate system for modelling and analysing of weather patterns and he developed a system based on a set of twelve linear equations that he would use to test various predictive models. The early outcomes run by his primitive computer were satisfactory and, as he expected, the weather repeated itself.

However, one day, he decided to examine one sequence of the model in more detail. He took the shortcut, and instead of starting the whole run over, he started midway through. To give the machine its initial conditions, he typed the numbers in it straight from the earlier printout. When he returned an hour later, he saw something unexpected. The new run should have exactly duplicated the old, but the weather pattern was rapidly diverging from the last run (figure 3.4). He repeated the test several times and only on the occasion when he did not type the shortcut numbers himself and the machine used its own database the result was as expected. Soon he realized that his computer's memory stored the data with six decimal places (e.g. 0.506127) but on the printout, to save space, just three of them appeared (e.g. 0.506) and in his shortcut modelling, he had entered the shorter one, rounded-off numbers, assuming that the difference was inconsequential (Gleick, 1987; Cooper, 2000; and Gribbin, 2004).

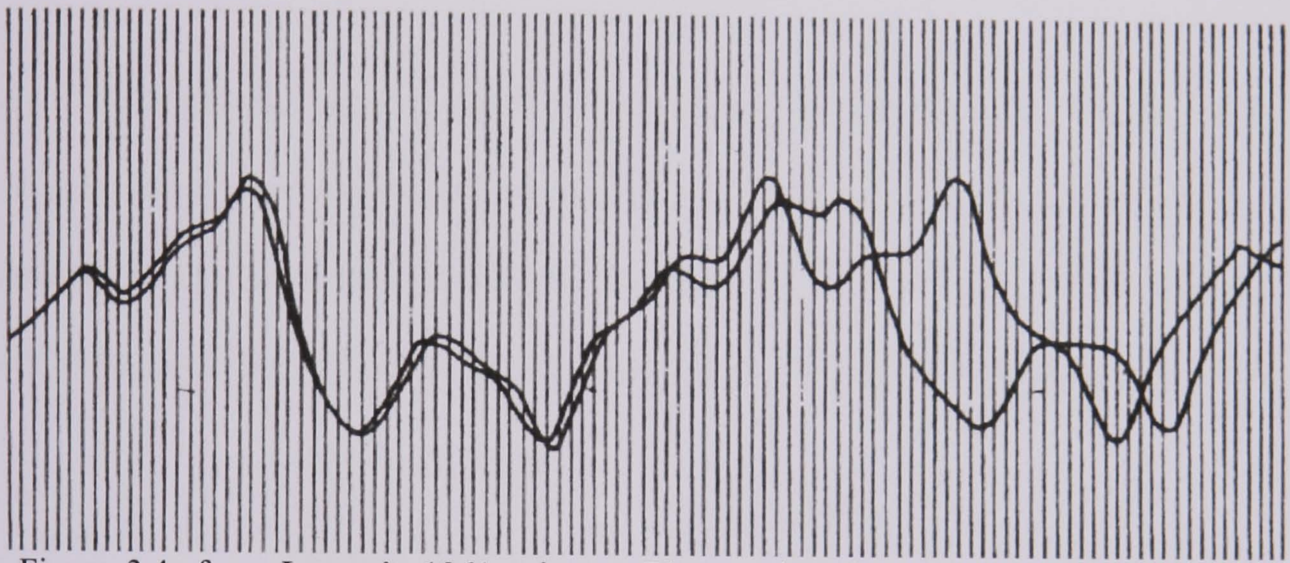

Figure 3.4: from Lorenz's 1961 printout, The graphs of what seem to be identical, dynamic systems appear to diverge as time goes on until all resemblance disappears. (Gleick, 1987, p.17)

Based on a Newtonian belief, small influences can be neglected, as they do not have large effects on the behaviour of a system. Lorenz, therefore, assumed that these minor changes could be ignored. However, in Lorenz's model, a small error proved to make a huge difference. Lorenz (1963) showed that the small change in the initial input – as small as one part in a thousand – was amplified in the course of two months' simulated weather until the difference was as big as the signal itself. Figure 3.4 illustrates how two weather patterns from nearly the same starting point, as Lorenz observed on his computer, produced patterns that grew further and further apart until all resemblance vanished.

'It was this observation that ultimately led to the concept of sensitivity to initial conditions and to the coining of the term Butterfly Effect' (Cooper, 2000, p.25). It means that very small variations in the initial condition of some systems result in huge, dynamic transformations in their consequent events. In weather, for example, 'this translates into the notion that a butterfly stirring the air today in Peking can transform storm systems next month in New York' (Gleick, 1987, p.8).

Bhutta (1999) wrote that, perhaps the most identifiable symbol linked with the Butterfly Effect is Lorenz's Attractor. Lorenz was looking for a way to model the action of the chaotic behaviour of a gaseous system. Hence, he took a few equations from the physics field of fluid dynamics, simplified them, and got the following three-dimensional system:

$$\begin{aligned} dx/dt &= \Delta(y-x) \\ dy/dt &= rx-y-xz \\ dz/dt &= xy-bz \end{aligned} \qquad \text{(Equations 3.1)}$$

If one were to plot these three differential equations on a three-dimensional plane, no geometric structure or even complex curve is produced; instead, a weaving object appears. Because the system never exactly repeats itself, its trajectory never intersects itself. Instead, it loops around forever. Figure 3.5 illustrates this phenomenon showing that the path through state space taken by Lorenz's attractor (the system's trajectory) never crosses itself. If it did so, it would return to an equilibrium state alike periodic system. Attractors of chaotic systems are called strange attractors. A strange attractor – like the one illustrated in figure 3.5 – never repeats itself on a similar path and therefore does represent a non-periodic (aperiodic) behaviour.

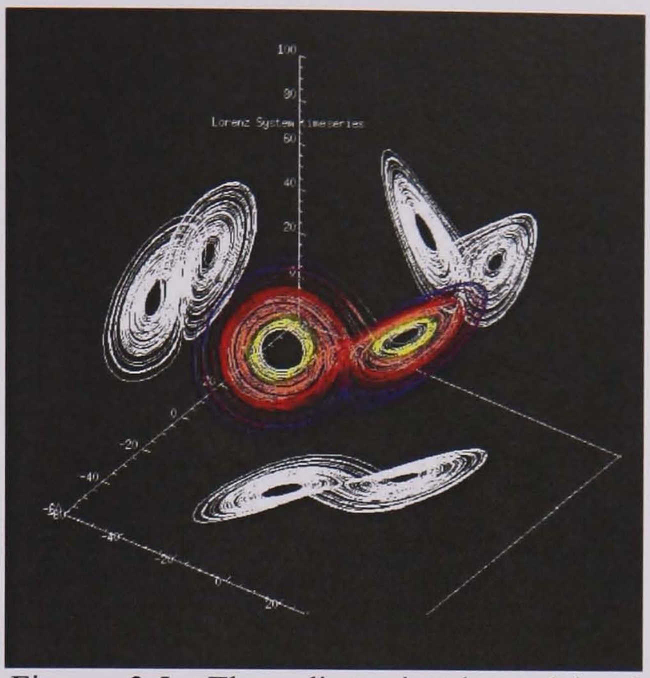

Figure 3.5: Three-dimensional model of Lorenz's attractor. (Bhutta, 1999, unpaginated)

3.1.2 Interpretations of Chaos Theory

> 'Chaos theory is the study of complex nonlinear dynamic systems' (Bhutta, 1999, unpaginated).

As discussed earlier, the word 'Chaos' as a scientific term conveys a meaning different from that to which the ancients referred, or even what we mean in everyday conversation today. In the conventional use, the term is defined as 'completely random and unpredictable even in principle', whereas the scientific use is 'nonlinear behaviour of a complex system with underlying deterministic order' (Valle, 2000, p.2), which is predictable in principle but limits our prediction in practice. Gribbin (2004, p.70) argued that 'it is just that in practice it is impossible to predict in detail what is going to happen more quickly than events unfold in real time'. For instance, as seen in Lorenz's work in weather forecasting, one would be able to predict such system just in a short term.

Before advancing into the more technical areas of chaos and complexity, it is useful to review some basic definitions suggested for 'Chaos Theory'. Although some individual attempts had been made by earlier scientists in studying chaos theory, it only became possible to understand it in the 1960s (e.g. through the work by Lorenz), with the advent of powerful and fast (by standards of those days) electronic computers. These new developments began to emerge into wider public awareness from the mid 1980s with the publication of the book titled "*Order out of Chaos*" by Ilya Prigogine and Isabelle Stengers (1984), and then of James Gleick's (1987) "*Chaos*".

Gleick (1987, pp.147-305) collected some formal definitions given by a diverse range of scientists, such as biologists, meteorologists, chemists, ecologists, economists, etc. Gleick (1987, p.307) wrote, 'whatever their particular field, they have made important contributions to understand complexity itself ... they believe that some systems that seem to have simple deterministic behaviour could breed complexity'. He added that such systems are too complex to be examined just by Newtonian laws of traditional linear mechanics.

A helpful commentary on the word "chaos" has been provided by Hayles (1991). According to her, whilst chaos, in its popular usage, is to be understood as a description of anti-order, to all intents and purposes as a synonym for randomness, in its scientific usage, chaos is seen as containing and/or proceeding order. Hayles (1991, p.1) also remarks that, 'in both literature and science, chaos has been conceptualized as extremely complex information, rather than as an absence of order'. She suggests that, while the word has its origin in the Greek for "void", the contrast between chaos as disorder and order is a continuing dichotomy in the western mind-set. One is concerned with the order that lies hidden within chaos (US based). The other, European based and represented particularly by Prigogine *et al* (1984), focuses on the order that emerges from chaos.

Chaos theory is a developing scientific discipline for studying nonlinear dynamics and complex systems. According to one of the clearest definitions given for "Chaos Theory" by Bhutta (1999, unpaginated), 'Chaos theory is the qualitative study of unstable aperiodic behaviour in deterministic nonlinear dynamic systems'. Bhutta (1999) explains that "aperiodic" is simply the behaviour that never repeats; "nonlinear" implies recursion and higher mathematical algorithms; and "dynamic" implies non-constant and non-periodic (time variables). Thus Chaos Theory is the study of forever changing complex systems based on mathematical concepts of recursion, whether in form of a recursive process or a set of differential equations modelling a physical system (Bhutta, 1999).

The most important feature of chaotic systems is that they are 'very sensitive to their starting conditions'. This is the character of many actual events in nature where small causes produce enormous consequences. As Gribbin (2004, p.3) suggests, what really matters is simply that some systems are 'very sensitive to their starting conditions, so that a tiny difference in the initial push you give them causes a big difference in where they end up'. This kind of behaviour is called "chaotic".

The other important feature of a chaotic system is that there is always positive and negative "feedback", so that what a system does, affects its own behaviour. This feature turns a system into becoming nonlinear. Therefore, chaos has been defined as nonlinear behaviour that occurs in complex systems. Grace (1991) wrote that "Chaos" is the study of a complex system with seemingly irregular and unpredictable behaviour rather than trying to reduce it to linear cause-and-effect relationships. Since most processes in nature are not linear, it is in fact, the study of how most things behave (Saunders, 1997).

This feature, together with other characteristics of chaotic complex systems, will be elaborated more in part two of this chapter. However, it should be emphasised here that all of the above definitions indicate a duality of order and disorder, which exists within the behaviour of a system considered as deterministic chaos. One of the best and classic examples demonstrating this duality can be found in the logistic equation developed by James Yorke, Robert May, and Mitchell Feigenbaum during 1970s. Explaining in detail what they found in their studies on population change occurring in nature, Gribbin (2004, p.72) declares that their studies are based on 'a very simple equation called the logistic equation':

$$\text{Logistic equation: } x_{n+1} = Bx(1 - x_n) \qquad \text{(Equation 3.2)}$$

The equation 3.2 describes well how the population of a species changes from one generation to the next and how 'the behaviour of a system can change from being completely ordered to being completely chaotic' (Cooper, 2000, p.33).

Simply, it can be assumed that there is some kind of insect population where a population contains x individuals and each insect lays B eggs. Therefore, the new #population will be Bx. However, what (1-x) implies is the fact that the process is nonlinear and acts as a controller parameter, which (in our example) represents the death rate. Gribbin (2004, p.73) wrote 'this death rate depends on the size of the original population – the more individuals there are, the harder it will be for each of them to get enough food and harder to survive'. The Feigenbaum diagram (figure 3.6) shows how the logistic equation behaves strangely with a small difference in values selected for parameter B that can be translated as a small change in the initial condition of the system.

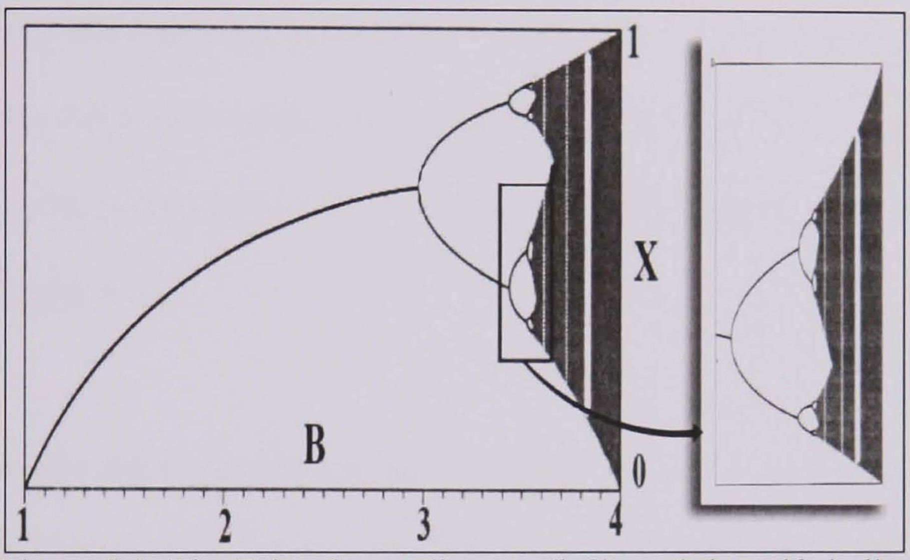

Figure 3.6: The Feigenbaum diagram (left), and the self-similar pattern in the period-doubling (right). (Gribbin, 2004, pp.76-77)

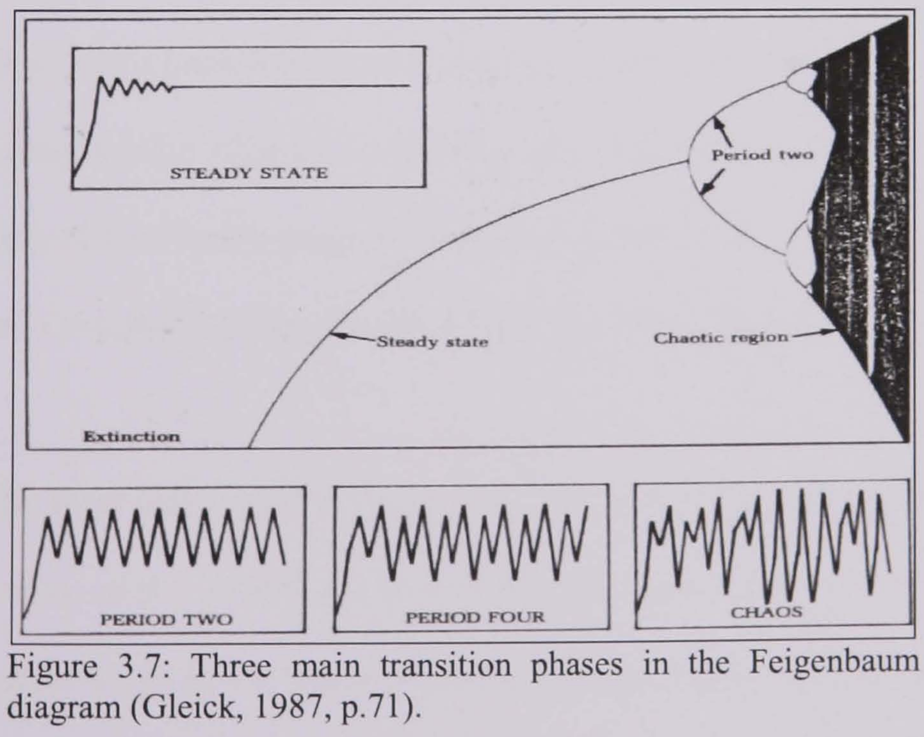

Figure 3.7: Three main transition phases in the Feigenbaum diagram (Gleick, 1987, p.71).

B = 0 means extinction. If B is less than 1, it means the population fails to reproduce itself from one generation to the next and it must eventually die out whatever the original value of x between 0 and 1. Interesting things happen when B is larger than 1. Figure 3.7 illustrates three transition states of the logistic equations when any larger value than 1 is selected for B. Each phase is explained well in Gribbin's (2004, pp.72-80) book, *Deep Simplicity,* which can be summarised as follows:

Phase one, steady state (period one): For $1 < B < 3$ after a large number of generations the value x settles down to a steady level and when it is close to (but less than) 3, value x settles down at 0.66, corresponding to 2/3 of the maximum possible population (see the steady state in figure 3.7).

Phase two, periodic state (period two up to period four): As soon as B is 3 or just a little larger than 3, the pattern changes and the single attractor splits in two levels in alternative generations (bifurcation). This means that in one year there is a large population, which eats all available food, resulting in many individuals starving and dying without reproducing. Therefore, the next generation has a small population, all of which find plenty of food and lay eggs – and so on. However, the single attractor only switches between two predictable constant levels (see period two in figure 3.7).

Phase 3, chaotic state (after period four): If B is increased further, the result will be amazing. At a value of $B = 3.4495$ the system oscillates between four different populations (period 4). At $B = 3.560$, each of these attractors splits in two again, and the population jumps about between eight different levels. At 3.569, another doubling gives sixteen possible population levels. Developments from May's early work show that at

3.56999 the number of attractors available to the populations becomes infinite: this is genuine deterministic chaos.

However, there is more. Although it is mostly chaos for values of greater than 3.56999, there are small ranges of values for B where order is restored, a kind of clear window among the confusion of the chaos. For 3.8< B <3.9 the system seems to settle down to a stable state and then, just for a little bit higher 3.9, once again repeated bifurcations can be observed, resembling the behaviour when B was just above 3. Soon, the system goes through all the same stages as before and chaos reappears. Interestingly, it can be concluded that 'in the midst of order there is chaos; but in the midst of chaos, there is order' (Gribbin, 2004, p.76). This statement conforms to the definitions presented earlier for the term "deterministic chaos" and suggested by Hayles (1991) and Gleick (1987). That is perhaps why Waldrop (1992) subtitled his popular book, *"Complexity"*, as "*The Emerging Science at the Edge of Order and Chaos*" by which he meant that the account of bifurcation in complex systems suggests that there is a domain between deterministic order and randomness, which is complex.

In short, two important outcomes can be concluded from the Feigenbaum experiment and the resultant diagram. Firstly, the experiment shows how the behaviour of a system shifts from being completely ordered to being completely chaotic and *vice versa*. Secondly, the Feigenbaum diagram (figure 3.7) reveals the self-similar pattern underlying its chaotic behaviour. As figure 3.8 illustrates, a smaller version of the pattern (at its smaller scales) in the Feigenbaum diagram is similar to the whole pattern (at its full scale). In other words, it repeats itself. These self-similar patterns are called *fractals*; in this sense, "Fractal Theory" can be understood as subset of chaos theory and can be called the "Geometry of Chaos/Complexity" which is the focus of part three of this chapter in part three.

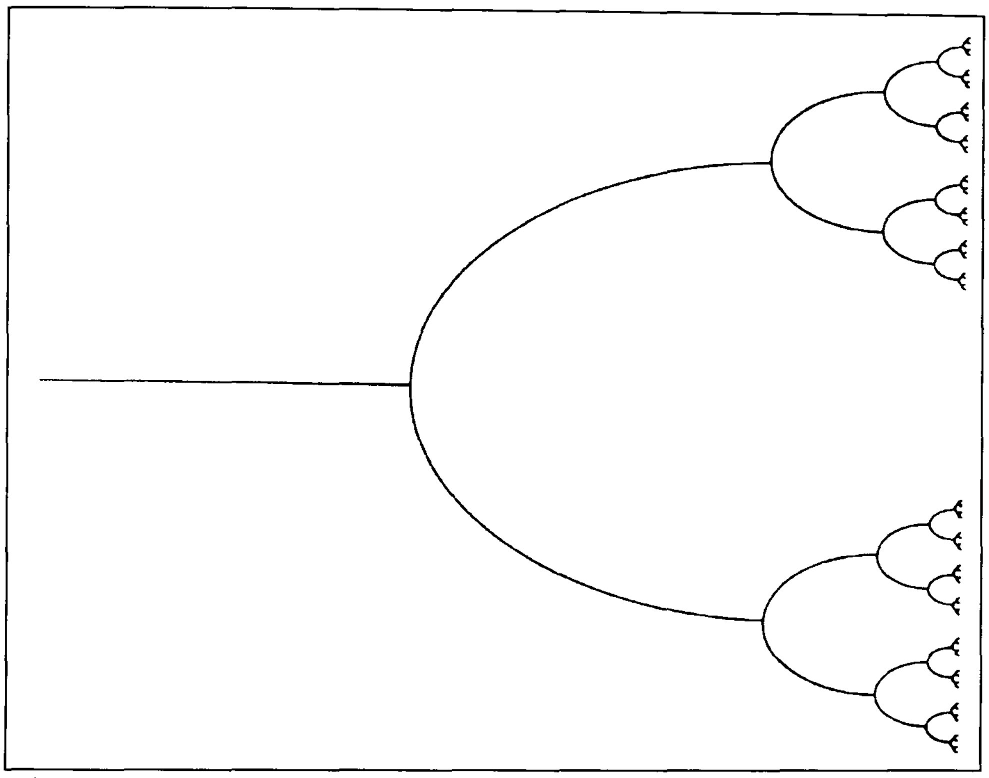

Figure 3.8: Simplified representation of self-similar branching seen in the Feigenbaum diagram. (Gribbin, 2004, p.80)

The final point about this example is that it clearly shows how chaotic behaviour appears out of a simple equation and with just one variable (B). 'Calculating all the iterations for just one value of B is boring enough, and in order to look closely at what happens near the critical value B=3, you need to carry out many iterations for many slightly different values of B' (Gribbin, 2004, p.75). Now imagine how hard it would be to calculate a complex system, which consists of many subsystems, each of which has more than one variable. This is straightforward enough to explain, but very tedious to calculate. That is perhaps why the study of chaos theory and fractals would not have been possible without the advent of computers.

3.2 Part Two: Complexity, Characteristics of Chaotic Complex Systems, and their Analogies to Urban Systems

The aim of this part is to define the term complexity and its suggested properties to verify whether the concept and its characteristics can be observed in an urban system. To achieve this aim, the research investigates through the literature, firstly to define the term and secondly to examine the properties of complexity in the work of complexity theorists (e.g. Gribbin, 2004; Philips, 1994; Flood and Carson, 1993; Cilliers, 1998). In parallel, it also explores the literature discussing the concept in urban studies in particular (e.g. Batty, 1994, 2005, 2008; Cooper, 2000; Byrne, 1998; Wilson, 2000; Alexander, 2002, 2005). The parallel review provides a backbone for the next chapter where the application of these theories to urban planning and design will be elaborated.

3.2.1 Complexity theory and its relationship with chaos theory

The concept of "complexity" as a technical term applies to a system that is entirely different from the familiar linear system encountered in Newtonian physics. It should be emphasised that the concept is not difficult or complicated but neither is it simple. Perhaps one should not be surprised if the concept cannot be given a simple definition. Batty (2008, p.8) recognizes the difficulty in finding a precise definition for complex systems, 'which lies at the basis of any attempt to understand such complexity'. Some suggested definitions are as follows. To begin with, Webster's Third International Dictionary (online, undated) proposes two following commonsense definitions for it:

1. Having many varied interrelated parts, patterns, or elements and consequently hard to understand fully.

2. Being marked by an involvement of many parts, aspects, details, notions, and necessitating earnest study or examination to understand or cope with.

According to Flood and Carson (1993, p.25), 'The definitions suggest that complexity can be understood by studying (1) the number of elements and (2) the number of relationships between the elements'. However, it should be noted that a complex system is not constituted merely by the sum of its components, but also by the intricate relationships between these components (Cilliers, 1998).

Williams (1997, p.234) suggested that 'a complex system is one in which numerous independent elements continuously interact and spontaneously organize themselves into more and more elaborate structures over time. Complex systems can naturally evolve to a state of self-organized critically, in which behaviour lies at the border between order and disorder'. In similar way, Ward (2003) suggests that "complexity theory" is the science of studying the interactions of local systems, which their organization as a whole is in transition between order and randomness (termed *edge of chaos* or *deterministic chaos*).

According to a definition given by Flake (1998), complexity theory is the study of how critically interacting self-organizing components form potentially evolving structures, exhibiting a hierarchy of emergent system properties. Luhmann (1995, p.25) suggests that 'complexity entails that, in a system, there is more than one possibility that can be actualized'. Complex systems can also be defined by the fact that they may be generated by a relatively simple set of sub-processes: a few things interacting, but producing tremendously chaotic behaviour. As the Nobel Laureate Murray Gell-Mann phrased it: "Surface complexity arising out of deep simplicity" (Gribbin, 2004).

A useful definition has been provided by Batty (2007). He states that 'a complex system is a system that is composed of complex systems. This recursion makes considerable sense when we ponder systems such as economies and cities for their elements – individuals – clearly have the same order of complexity as any aggregation in groups or institutions' (Batty, 2008, p.2). He also suggests that complexity can be understood mathematically in the same way that the simple rule and randomness coexist in the logistic equation (equation 3.2) – as explained earlier in the previous section. He suggests that complexity can be demonstrated through the notion of variety, defining a system in terms of a number of components, say n, and the number of states, say m, which each component can take on. The simplest demonstration is to compute the number of combinations of states when a state can exist or not, given by the combinatorial C:

$$C = \sum_{n=1}^{k} (n!k!(n-k)!) \qquad \text{(Equation 3.3)}$$

> 'This number of combinations could be elaborated in countless ways and although it can be reduced simply by introducing constraints on what is feasible and what is behaviourally acceptable, it is still huge and to all intents and purposes infinite. This is one of the key challenges of complexity theory: understanding, grappling, and managing this sort of combinatorial explosion' (Batty, 2008, pp.8-9).

The above equation is probably the best, and mathematically the simplest, expression of complexity, which explains chaotic behaviour of a system governed by many subsystems. Subsystems interact among each other in a nonlinear manner. As a comment on the equation 3.3, one could say that, (1-K!) or n!(n-k)! shows the *"recursive property"* of a system – also called the *"positive feedback"* (Flood and Carson, 1993). It means that when a criterion increases or when a subsystem progresses within such system, there is always one or some other criteria\subsystems, which progress in the opposite way to control the overall behaviour of the system. They may prevent its further progression to help the whole system remains stable. A control system must have adequate variety or, as Ashby (1973) called it, "*the law of requisite variety*", 'if the system is to have guarantee of remaining under control' (Flood and Carson, 1993, p.15).

Comparing equations 3.2 and 3.3, one can see clearly the similarity and difference between chaos and complexity. "$\sum$", in the latter equation, discloses the difference between them. While chaos theory is about the strange behaviour occurring in one chaotic system, complexity theory is about the interactions between multiple chaotic systems controlling each other to create a variety of states within a bigger system. That is perhaps why Batty (2008) states that a complex system is a system that is composed of complex systems. In this sense, as Ward (2003) suggests, chaos can be considered as the subset of complexity.

The definitions suggested for "complexity" usually associated with the terms synthesis, cross discipline, edge of chaos, nonlinear dynamics, self-organising systems, etc (see Appendix A for their definitions). Each of these terms conveys an aspect of complexity. However, the concept remains elusive as the given definitions constrained its full meaning. According to Batty (2007), while there is no single widespread agreement as to precise definition, there is a consensus about the definitions of the characteristics that a complex system displays. Therefore, instead of trying to coin a single definition for the term, an analysis of characteristics of complex systems can be attempted in order to develop a general understanding of the theory.

3.2.2 Characteristics of complex systems, and their analogies to urban systems

While some theorists reduced the properties of complexity to only two main features of chaos, '*sensitivity to the initial conditions*' and '*feedback*' (e.g. Gleick, 1987; Gribbin, 2004), some other complexity theorists believe that a system must associate with more features to be considered complex. For instance, Durlauf (2005), himself a mild sceptic of complexity theory, identifies four key features, which such systems must portray to be seriously considered as complex: *non-ergodicity, phase transition, emergence,* and *universality* (see also Batty, 2008). Valle (2000, p.4) suggests six characteristics for such system and states that complexity can be characterised by:

a) A large number of similar but independent elements or agents

b) Persistent movement and responses by these elements to other agents

c) Adaptability so that the system adjusts to new situations to ensure survival

d) Self-organization, in which order in the system forms spontaneously

e) Local rules that apply to each agent

f) Progression in complexity so that the system gradually becomes larger and more sophisticated

However, Cilliers (1998, p.4) provided a rather more complete list and outlined ten characteristics for a complex system. According to his list, complex systems have "a large number of elements" (1), which have to interact "dynamically" (2), and are "richly connected" to each other (3). The interactions are also "nonlinear" (4). Such interactions usually have low range (local interaction) although long-range (global interaction) is not impossible (5). There are loops in the interactions termed "recurrence" or "feedback" (6). They are usually "open systems" which interact with their environments (7). They are far from equilibrium with "phase transition" (8). They have history and "evolve" through time (9). Finally, each element has limited capacity of information (locality of information) which is ignorant of the behaviour of the system as a whole (10).

Identifying a series of eight features for complexity – "Unpredictability", "Emergence", "Self-organization", "Irreducibility", "Adaptability'', "Interconnectedness", " Complexity through Rules", and "Form Versus Process" – Cooper (2000, p.8) suggests that 'all can arguably be observed in the city' too. A similar vocabulary has been found in work of those authors who suggested cities are to be considered as self-organising complex systems (e.g. Batty, 2005, 2008; Portugali, 2000; Wilson, 2000). According to what have been used commonly and frequently in the literature, this research suggests that the following 12 characteristics of complexity are essential in understanding of the theory.

1- Variety (Large number of components with dynamical interactions)

2- Irreducibility

3- Deterministic chaos (duality of determination and randomness)

4- Positive and negative feedback

5- Sensitivity to initial conditions (the butterfly effect)

6- Limited predictability

7- Emergence

8- Self-organization

9- Adaptability

10- Interconnectedness (Synergy)

11- Hierarchy and levels of scale

12- Self-similarity and fractal pattern (the image of complexity)

3.2.2.1 Variety (Large number of components with dynamical interactions):

Complex systems consist of a variety of subsystems or a large number of elements. When the number is relatively small, the behaviour of the elements can often be given a formal description in conventional terms. However when the number becomes sufficiently large they cease to assist in easily understanding the system. Cilliers (1998, p.3-4) states that 'a large number of elements are necessary, but not sufficient. ... in order to constitute a complex system, the elements have to interact and this interaction must be dynamic'. He adds, 'the interactions do not have to be physical; they can also be thought as transference of information'.

Therefore, the grains of sand on a beach do not make a complex system, because although they are numerous there is no interaction between them. Conversely, in a complex system such as Lorenz's weather model (discussed in section 3.1.1.3), the system consists of differential equations (equations 3.1) which interact dynamically and make the system change with time. According to Cilliers (1998, p.6), the most obvious example can be seen in the economic system of a city as 'the economically active people in a city certainly comprise a large amount of elements, usually several millions. The various individuals interact by lending, borrowing, investing and exchanging money and goods. These relationships change continually'.

3.2.2.2 Irreducibility:

> '2+2 ≠ 4; rather 2+2 = apples' (Morgan, 1923; quoted by Jenks, 1997, p.61).
>
> 'A non-linear system cannot be reduced to its components parts because the whole pattern, due to its interconnected nature, cannot be seen as a single element' (Cooper, 2000, p.10).

Another feature of nonlinear complex systems is irreducibility. While a complex system consists of a large number of elements, components, or subsystems, it cannot be reconstructed by simply adding its elements together. The notion that in general systems theory known as "gestalt" implies that system structure emerged from the parts but that is not simply a process of adding up the bits to get the whole (Batty, 2008). The whole system is more than sum of its parts, and as the Nobel laureate Philip Anderson (1972, p.393) wrote, 'more is different'. Examples can be found in many biological, ecological, and sociological phenomena. A human being is not an aggregation of bodily parts, nor is a business an aggregate of management functions, nor a society an aggregate of social groups. In each case, things come together to form 'wholes' whose properties are different from the parts.

In all complex phenomena, the "wholeness" is the important thing. According to Alexander (2002a, p.80), 'the local parts exist chiefly in relation to the whole, and their behaviour and character and structure are determined by the larger whole in which they exist and which they create' life or quality. The implication is that, in complex systems, we are dealing with systems that have purposeful parts and some final worth – or intrinsic quality – and for which traditional reductionism is inappropriate. The holistic approach rejects the modernist mechanical view of a city in which the position of every element can be determined in advance and their composition creates the entire city (the failures of reductionism view in modernist planning will be discussed in more detail in chapter four).

For instance, Cooper (2000, p.10) suggests that 'land use zoning as planning tools represent a form of reductionism, isolating what should be, in a non-linear system, a "linked element", thus breaking the linkage that would make the area richer and more diverse'. Another example has been suggested by Meijers (2008, p.2323) who states that 'summing small cities does not make a large city'. His research reveals that the more polycentric a region is – as opposed to mono-centric – the fewer cultural, leisure and sports amenities are present.

3.2.2.3 Deterministic Chaos (Duality of Determination and Randomness):

> Einstein's famous question: 'Does God plays dice with the universe?'
> (Gleick, 1987, p.314)

As discussed in the previous part of this chapter, the behaviour of the agents in a nonlinear complex system is neither completely deterministic nor completely random; indeed, it exhibits both characteristics. This duality is termed deterministic chaos or 'complexity through rules' (Cooper, 2000, p.11). While a simple deterministic system with only a few elements can generate random behaviour, in a complex deterministic system, random behaviours are generated without violating the overall rules of the whole system (Crutchfield *et al,* 1988). On the one hand, it allows us to bring increasingly into the deterministic framework of classical science broad areas of phenomena; on the other, it represents a limit to the complete testability of the classical paradigm, which seemed to resist such inclusion.

This means that there are some ruling equations, which determine the system's behaviour – the way agents interact – and preserve the quality, the position, or the general character of the system. Cooper (2000, p.11) suggested that the source of order in the case of a city 'could be planning policies, building regulations, rules governing of granting financial credits', etc, all of which will determine the behaviour of the system. Nevertheless, at the same time, random behaviours are also allowed within the limits set by such regulations. The main source of the randomness – but not exclusively – is unpredictable decisions and actions of human users (individuals or communities) as free agents who act within the rules' limits in an urban context. For instance, every time designers (who are also human) make a decision to change or not a shape; add, move or remove an event; or rearrange overlaps, they are creating completely new interface patterns (Arida, 2002).

3.2.2.4 Positive and Negative Feedback:

Feedback is the most important feature characterising a complex system. This feature is also called the "recursion" or "recursive property" and can be described mathematically as seen earlier in the equations 3.2 and 3.3 (represented by 1-x or n-k!). Feedback describes the consequences of change in a system. It means that feedback occurs where the behaviour of an element influences on the way other elements act or react, but through a series of relationships, the effect of its initial influence feeds back on itself.

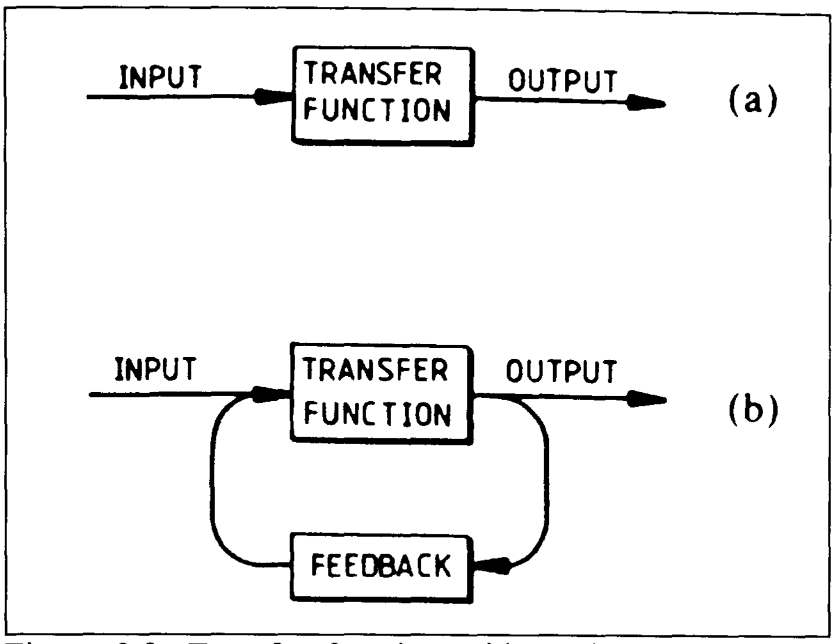

Figure 3.9: Transfer function without feedback (a) and with feedback (b). (Flood and Carson, 1993, p.14)

If those mechanisms that create a behaviour are lumped into a single "transfer function" (TF), Flood (1993) claims that in a linear relationship the action on an input produces an output without receiving any feedback from TF (figure 3.9a). However, in a non-linear relationship, the output is used as the input in the next calculation (figure 3.9b). As the positive or negative feedback (depending on the type of TF) occurs repeatedly, the system reaches a critical threshold far from equilibrium, which moves from a phase state to another – phase transition – while returning to the initial state becomes impossible (Batty and Xie, 1999). That is why Cilliers (1998, p.4) claims that 'complex systems have a history' (e.g. in the case of a city, the transition from agricultural city to industrial city).

Feedback occurs in all nonlinear systems but not all systems with feedback are nonlinear. While positive feedback can cause instability in a nonlinear system, negative feedback tends to stablise such a system. The insect population model (explained earlier in section 3.1.2) is an example of a nonlinear system with negative feedback. As soon as the population of insects increases, the portion of available food for each insect decreases, which feeds back and controls the population of insects, stabilising it, bringing it back close to earlier numbers (but not exactly the same), and allowing the system to return to its balance. If the output numbers are not exactly the same as the earlier conditions, this balance is fragile and the system keeps its nonlinearity. If the negative feedback brings the output of the system back exactly to the initial condition of the system, the system lose its nonlinearity and turns to a linear periodic status.

However, According to Byrne (1998, p.172), the significance of positive feedback – as opposed to negative feedback – 'is that it is not boundary defending, but is likely to lead to boundary breaking and transition to a new phase state'. Flood and Carson (1993) believes, positive feedback helps to achieve contained contraction or replication and growth or leads to uncontained and unstable contraction or growth. It should be also noted that 'positive feedback occurs when a change tendency is reinforced rather than damped' (Byrne, 1998, p.172). As seen in the Lorenz's weather model, 'the butterfly effect is an example of series of positive feedback within the system' (Cooper, 2000, p.8).

Positive feedback may be desirable but can be lead to structural changes and possibly to structural collapse. Both desirable and undesirable cases are illustrated in the following example:

> 'When we run, we need to increase oxygen intake and lung ventilation by increasing respiration rate. Positive feedback loops in the body temporarily dominate bringing about desirable increase in respiration that enables the running to happen. In healthy people, however, the limits of human capability are dictated by negative loops, so that we can only run so far for so long. This is for our own good and prevents us from burning out. If the negative loops are broken leading to an undesirable domination by positive ones, as happens when athletes take certain types of drugs, super human achievements can be realized. The history books report a number of tragic cases where the biological processes of [these] athletes may lead to collapse and death' (Flood and Carson, 1993, p.15).

In the case of a city, Arida (2002, p.153) claims that, human users are the main source of feedback: 'through their interpretation of interface patterns in their environment they act or react – from the simplest act of planting a tree (to embellish their front yard) to that of shopping (in response to a well-lit shop window display, for example). Eventually many people react similarly, building up into a resonance that can, for instance, affect the investment value of real estate, with all its physical consequences ....'

3.2.2.5 Sensitivity to Initial Conditions (The Butterfly Effect):

One of the most essential features of a chaotic system is what Lorenz (1963) called 'the sensitivity to initial conditions'. This means that infinitely small changes in the starting condition of a complex nonlinear system will result in dramatically different outputs for that system. An example of this, known to the world as The Butterfly Effect, was explained by Lorenz's experiments while he was formulating his model for weather forecasting (see Gleick, 1988, pp.16-32). It describes how a tiny action such as the flapping of a single butterfly's wing in the Indonesian coast, can be magnified through a month's time of cause and effect process, resulted in a hurricane hitting Miami rather than its expected target of Fort Lauderdale, for example.

Hamdi (2004) discusses the ingenuity of the improvisers and the long-term, large-scale effectiveness of immediate, small-scale actions. In the case of a city, a series of cause and effect processes of change often starts with small beginnings, which have emergent potential - as small as a bus stop, a pickle jar, a composting bin, or a standpipe. As an example, Hamdi (2004, pp.73-76) explored the emergence potentials of a bus stop to act as an initiator of other positive effects cultivating a community and writes:

> 'We had observed elsewhere the density of life and commerce which clusters around places where buses stop. People gather and wait for substantial periods and so, often, and in small steps, small shops and coffee houses will open to serve them, shoeshine boys and other street hawkers will appear... and spread their baskets on the ground to sell what they can to passer-by while they wait. At first, a small market emerges....'

No one designed this market place, which has the potential to motivate a vibrant community which sprouts, and grows around it. It can eventually turn to be a local centre or even, through some positive effects, improve housing, health, and education in that area. All these huge changes originate from small and often simple beginnings, which even though small, they are many, acting in order to induce others to act.

The bus stop example in an urban system is analogous to The Butterfly Effect in a weather system. Byrne (1998) explains that it occurs when a small apparently insignificant change in one agent has a knock-on effect on another agent, that is in turn has an effect on another agent, that in turn has an effect on another and so on in a multiplier effect with the potential result of a massive change occurring to the system.

3.2.2.6 <u>Limited Predictability:</u>

> 'The only limit to our realization of tomorrow will be our doubts of today'.
> (Franklin D Roosevelt, quoted in Hamdi, 2004, p. xv)

Chaos imposes fundamental limits on prediction. If we could know exactly the laws of nature and the precise situation of a system at its initial moment, we might be able to predict exactly the situation of that system at a succeeding moment – as Laplace had claimed (discussed earlier in section 3.1.1.1). However, this precision does not exist in real systems. There is always uncertainty about the outcomes of processes of change that originate from the bottom up (Batty, 2005). A very small diversion at its initial condition

– not at once but gradually – is turned to a huge diversion. Therefore, we might arguably be able to predict a chaotic complex system in the short term but not definitely in the long term.

According to Waldrop (1992), when the number of elements/agents increases, it becomes even more difficult to predict accurately the outcomes of their interactions. Referring to Waldrop's (1992) statements, Cooper (2000, p.8) suggests that 'cities have a large number of interdependent agents which makes them unpredictable'. Therefore, the ultimate shape of the city as a product of unpredictable actions and interactions between these elements/agents is also unpredictable. Batty (2005) states that the conception of the city as a complex system changes from one where we assume that all things about the system are ultimately knowable to one where this assumption is no longer tenable. The notion of limited predictability of the urban system calls into question the conventional planning approach of master planners who attempt to apply determinist blueprints for cities (see Chapters Four and Five for details).

3.2.2.7 Emergence:

'Emergence is a characterisation' (Flood and Carson, 1993, p.18).

Complicated and unexpected patterns and behaviour emerge within complex systems with no apparent cause or design (Waldrop, 1992). Having explored some of the attributes of a complex system, Cilliers (1998, p.91) stated that 'the system's individual components only operate on local information and general principles. The macroscopic behaviour emerges from microscopic interactions that by themselves have very meagre information content (only traces) but after simple interactions this results in complex behaviour when viewed macroscopically'. Cilliers (1998) interprets this behaviour as the emergent property of a system as a whole, and Alexander (2002b) called it "unfolding wholeness".

According to Alexander (2002b), the wholeness occurring in space necessarily unfolds in such way as to create more and more life and, through these transformations, larger wholes are created. "Emergence" means that new systems appear with new properties, which are not to be accounted for either by the elements into which they can be analyzed, or by the content of their precursors (Alexander, 2002). That is, perhaps, why no two complex systems are alike (Flood and Carson, 1993), or no two cities are exactly alike, even if they have a similar history. For instance, each Roman colonial city had its own identity while its overall layout follows the '*castra*' pattern, as discussed in chapter two.

Philips's (1994) work on features of complexity provides an example to illustrate emergence in the form of a residential segregation model constructed by Schelling (1969, 1978):

> 'A grid of squares represents homes in a mixed community made up of two groups of residents. At each prescribed period each household make a decision to stay or move to another square based on a programmed preference for living next to households of the same group and, as the time periods pass, pattern of residential segregation emerge. These pattern were not designed, they emerge by the action of a rule.... In the same way, the land-use of Oakland, California, emerge from the many decision taken by individuals influenced by the market, politics, the environment, fashion etc' (Cooper, 2000, p.9).

The emergent pattern demonstrated in Schelling's model is a classic example of how global order and unpredictable spatial pattern emerges from the bottom up and from the random actions of highly localised neighbourhoods. Batty (2005, 2008) and Silva *et al*

(2005) presented a simulated version of this model using *Cellular Automata* (CA). In their experiment, two social groups in the Schelling model are rendered in red and green on a fine lattice of cells. Then some simple rules are programmed at neighbourhood scale for making decisions (e.g. based on a preference for living next to the households of the same group), each cell maintains its initial colour state or converts into the other (each household decides to remain, or move). As illustrated in figure 3.10, after running the iterative program, unpredictable patterns of segregation emerges out of the initial random distribution of red and green cells.

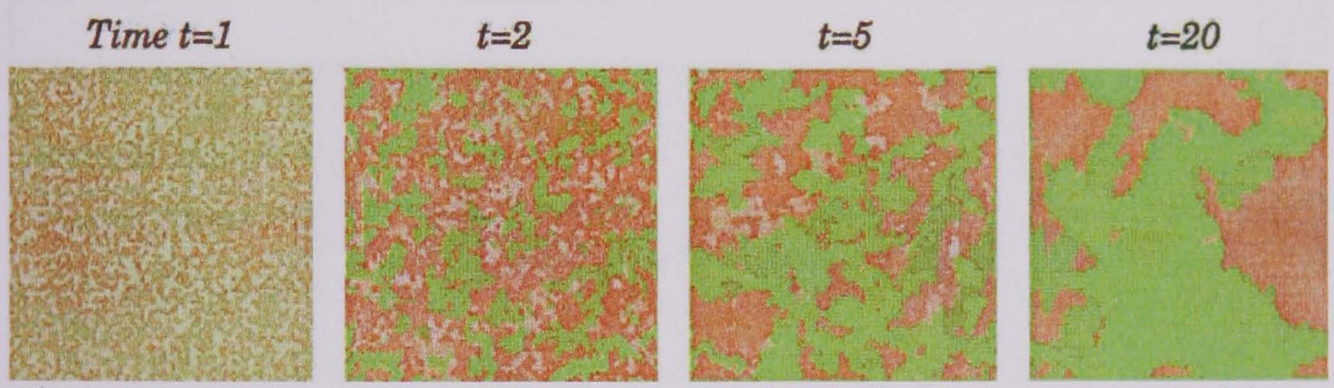

Figure 3.10: Emergence of extreme segregation from local cellular automata rules implying a mild preference for living amongst one's own kind. (Batty, 2008, p.17)

3.2.2.8 <u>Self-organization:</u>

> 'The capacity for self-organisation is a property of complex systems which enables them to develop or change internal structure spontaneously and adaptively to cope with, or manipulate, their environment' (Cilliers, 1998, p.90).

As Cooper (2000) stated, not only does a complex system as a whole emerge, but its structure and organisation also apparently emerge without pre-design. It means that the structure and behaviour of such a system is not determined in a preliminary way by the properties of individual components of the system, but are the result of complex patterns of interaction between itself and its environment. 'An example of self-organization in city growth is the development of local governmental systems. These were not simply designed and then implemented, they evolved, and changed, self organizing in response to changing needs, particularly in terms of safeguarding public health and welfare.' (Cooper, 2000, p.9)

Complex systems require a form of control mechanism to maintain their integrity (Flood and Carson, 1993). They can self-organise through their own controlling centres of their subsystems. Alexander (2004, p.328) claims that the whole system 'controlled by the field of centres, is not made up by rearranging fixed components. It is a structure which allows the evolution of space itself, a process in which the space changes qualitatively, step by step, through the intensification of the centres in it'. The intensification of the centres in subsystems means that a complex system becomes more complex through an evolutionary process.

This increase in complexity implies a local reversal of entropy – created by the recursive process or feedback – that necessitates a flow of energy or information through the system. The information is stored in forms or patterns within the system, conveying a kind of memory (Cilliers, 1998). If this information conforms to new circumstances, it is stored, and even enhanced; otherwise, it fades away, and is replaced by new information or a new pattern. Therefore, a self-organizing system always has a history. This may also form part of the explanation why self-organising complex systems tend to age. One of the obvious examples can be observed in the street patterns of a city. Old urban plots are sustained only if they can serve a new population with new needs; otherwise, they are changed, evolved, or replaced gradually by new sized plots in response to adaptations to a changing environment.

3.2.2.9 Adaptability:

Self-organizing complex systems have the ability to adapt to new situations in their environments. Adaptation is the result of evolutionary processes whereby a system will simply not survive if it cannot adapt to new circumstances. Flood and Carson (1993, p.13) wrote that:

> 'Darwinian evolution of life forms is a theory of adaptation. Similarly, certain management and organization theory has argued that a commercial firm needs to adapt to external changes – e.g. adaptation to changes in demand patterns, competitors' actions, and technological change; and to significant changes on the international scene like oil price increases or cuts, and wars. Adaptation is necessary for survival where the environment is subject to change. Adaptation occurs to deal with environmental change. If an environment is largely constant, then a system's survival is not threatened. But in other circumstances, changes in an environment will occur and throw the system out of balance.'

Mixed-species woodlands are an ecological example of an adaptable system that safeguards the survival of the whole system by allowing for change through variety. A mixed woodland can respond to climate change more readily than single-species woodland. If a change takes place that destroys one species, then the system as a whole will be affected but not destroyed, as another species will fill the gap left, either as an immigrant to the system or by expanding within the system. If the same destruction was to occur in a single-species plantation, the whole system will be destroyed. Cooper (2000, p.10) draws an analogy between single/mixed-spices woodland and single/mixed-use zone in a city and writes:

> 'Translating this ecological example to urban design, the single-species area could relate to single-use zone in a city, or a company town, if its economic base collapses then so does the area as a whole, it then requires a larger scale alteration to again become viable. Eventually the city as a system will re-colonize the area but it will take much longer than if the area had contained a mixture of uses and building types.'

The unpredictable morphological change occurring in 'a redevelopment of a plot or a series of plots within the existing street system without the introduction of new streets' – known in Conzenian terminology as *'adaptive redevelopment'* – explicitly reveals the ability of a city system to adapt to the new situations in its environment (Larkham and Jones, 1991, p.13; see also Conzen, 1962). Figure 3.11 illustrates an example of adaptive redevelopment, in which the street system has evolved without pre-design in respond to changing uses over time.

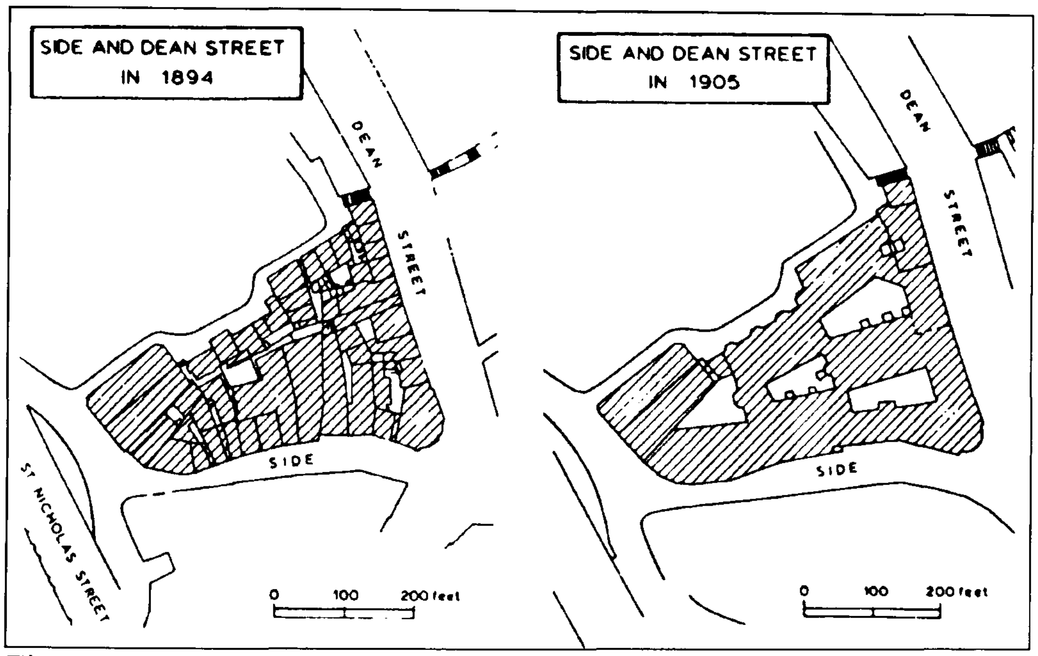

Figure 3.11: Adaptive redevelopment in central Newcastle upon Tyne (Larkham and Jones, 1991, p.13)

3.2.2.10 <u>Interconnectedness (Synergy):</u>

> 'Cities present situations in which several dozen quantities are varying simultaneously in subtly interconnected ways' (Jacobs, 1961, p.433)

Another feature of nonlinear complex systems is interconnectedness. It indicates a quality similar to what is called synergy in management and organisation theory referring to the benefit of group working (Flood and Carson, 1993). The components of a complex system are connected closely together at the local level and to the environment at the global level (figure 3.12). Philips (1994, p.6) writes that 'a nonlinear system is woven into its environment so closely that we now speak of co-evolution – the system, and its environment evolving together' (quoted in Cooper, 2000, p.10).

Jane Jacobs (1961) argued that a city is fundamentally a living organism with complex inter-linkages and holistic behaviour. Alexander's theory of pattern language describes well the interconnectedness characteristics of a city system. Alexander *et al* (1977) suggested that buildings, neighbourhoods, cities, and metropolis, are the product of a language of patterns. According to his theory, doors, windows, buildings, squares, neighbourhoods and cities, are interconnected by "patterns" in a way similar to words, concepts, sentences, paragraphs, chapters, and stories. A natural spoken language has a set of elements (words), and a set of rules, which define the possible arrangements of words. In an urban context, 'each pattern is a rule, which describes the possible arrangements of the elements' and even the arrangements between patterns (Alexander, 1979, p.185). As in spoken language, the built environment is the product of a conversation between a large number of elements and pattern languages, which are the means with which they are interconnected.

3.2.2.11 Hierarchy and levels of scale:

> 'It is not the complexity itself that is important; it is the level of that complexity that is important' (Cooper, 2000, p.11).

A complex system self-organises by creating an ordered hierarchy of interconnections on several different levels of scale. Figure 3.12 shows a hierarchical organization at a number of levels, which is a logical representation of complex phenomena as systems of subsystems. A simple example of a hierarchic structure can be observed in a city street network. The organisation network formation follows a strict order: starting from the smallest scales (footpath), and processing up to the higher scales (roads of increasing capacity).

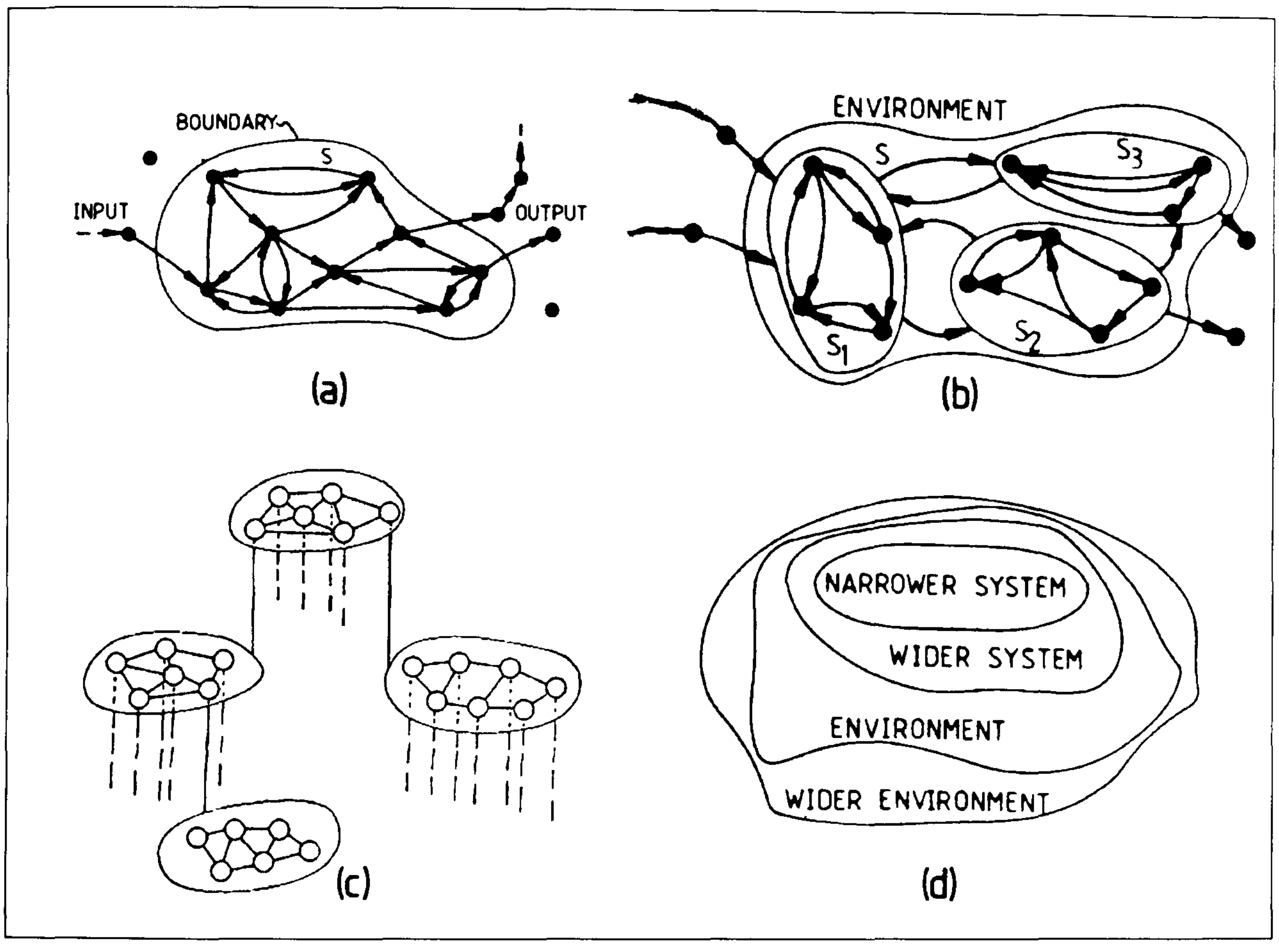

Figure 3.12: Interconnectedness and levels of hierarchy. a) A subsystem, b) a complex system of some sub-systems, c) the hierarchy of complex systems within an environment, and d) the hierarchical environments within a wider environment. (Flood and Carson, 1993, pp.9-17)

However, a hierarchical structure does not always create complexity. Alexander (1965) defined two types of hierarchy: the tree and the semi-lattice. Both the tree and the semi-lattice are ways of thinking about how a large collection of many small elements or sub-systems goes to make up a system with hierarchical structure, but only the latter leads to complexity. In the tree structure, each subsystem is fully independent from all other subsystems of its level, and it can thus interact with them only via higher order subsystems (figure 3.13, right). In the semi-lattice structure, however, there are overlaps between subsystems of the same order, so that interaction can occur vertically, horizontally and in oblique fashion (figure 3.13, left). As noted by Alexander (1965), it is not only the overlap which makes the difference, but more importantly, the semi-lattice is potentially a much more complex and subtle structure that the tree. He writes:

> '... a tree based on 20 elements can contain at most 19 further subsets of the 20, while a semi-lattice based on the same 20 elements can contain more than 1,000,000 different subsets' (Alexander, 1965; quoted in LeGates and Stout, 1996, p.122).

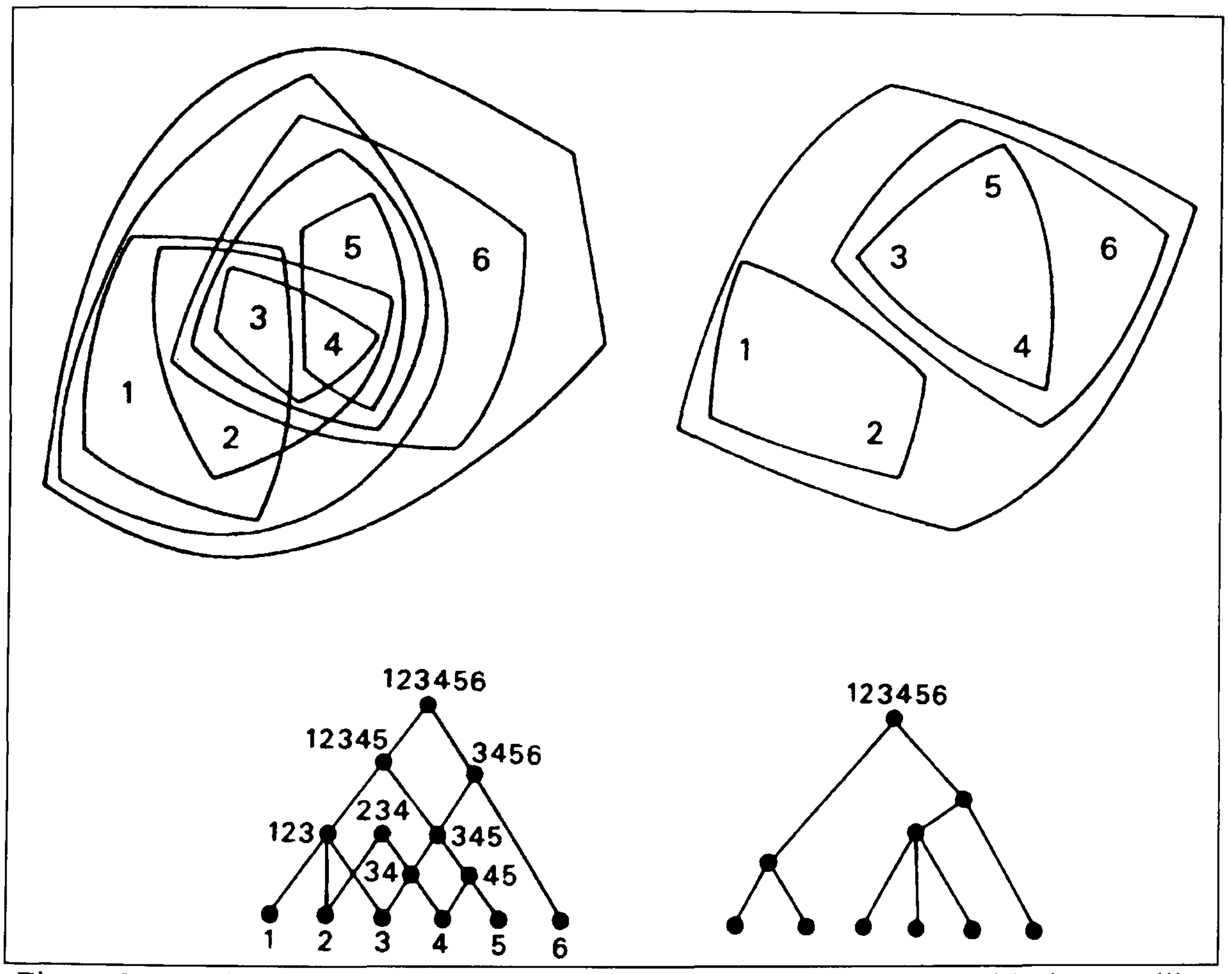

Figure 3.13: Alexander's semi-lattice hierarchy (left) as compared with the tree-like hierarchy (right). (LeGates and Stout, 1996, p.122)

Such a hierarchy (the semi-lattice) can rarely be established all at once, and if any connective level is missing, the urban web is pathological (Salingaros, 2005). This also echoes Jane Jacobs' (1961) notion about 'problems in organised complexity' in which, 'those areas seen as unsuccessful will be those that have source-rules that break down or simplify the natural level of order necessary for healthy urban development' (Cooper, 2000, p.11). Alexander (1965) claims that our modern attempts to create cities (e.g. Levittown, Chandigarh, and the British New Towns) create mostly a tree like hierarchy and therefore are less successful as compared to those with semi-lattice structures which have arisen more organically over many, many years (e.g. Siena, Liverpool, Kyoto, and Manhattan).

3.2.2.12 Self-similarity and Fractal pattern (the image of complexity):

From a morphological point of view, the most interesting characteristic of a chaotic complex system – and probably the most important one – is self-similarity, which has been termed 'fractal' by Mandelbrot (1983). Gleick (1987, p.103) wrote, 'Self-similarity is symmetry across scale. It implies recursion, pattern inside of pattern.... when a chaotic system is represented graphically, the resultant object is fractal'. Symmetry across scales means that the patterns or images that appear at each level of scale in a complex system are self-similar to the whole. The elements, which form these patterns, are interconnected in a nonlinear way exhibiting non-integer dimensions not explicable by Euclidean geometry. This is the geometry of nature (Mandelbrot, 1977, 1983); the image of chaos (Gleick, 1987, 1990); or 'the geometry of complexity' (Alexander, 2002b, p.180).

All complex systems consist of such patterns with 'generated structure'. According to Alexander (2002b, p.180), 'it is a fundamental law for creation of complexity' and he explains that 'a generated structure is something that has a certain deep complexity and is created in some way that appears to be almost biological, and reaches deeper levels of subtle structure than those we commonly associate with design or designed objects. This is the particular visible physical character of complexity. It may be identified as the sign that a complex system has been made by a generated and nonlinear process.

A clear example of the process of generating fractal patterns can be observed in the logistic equation. In part one of this chapter, it was explained that such a pattern is the result of the feed back process in an open system. As shown earlier in figure 3.8, the patterns on smaller scales are similar to the original pattern appearing as a whole. In other words, the whole pattern repeats itself at its smaller scales. Bhutta (1999, unpaginated) writes:

> 'Mathematically, fractals are pictures that result from iterations of nonlinear equations, usually in a feedback loop. Using the output value for the next input value, a set of points is produced. Graphing these points produces images. Again, by creating a vast number of points using computers, mathematicians discovered these wonderfully complex images, which were called fractals.'

Barnsley (1993) suggested that the examples of fractal patterns could be found everywhere from the microstructure of organisms, bacteria, crystals, flowers, feathers... to mega-structure of clouds, Mountains, coastlines, galaxies, etc. In the introduction of his book, *Fractals Everywhere*, he claimed that 'one would see everything differently, once he could speak with the new language of fractals'. As this property of complexity is our focus, the definition, meaning, and examples of fractal geometry in real life – in general – will be explained in the next part of this chapter and its application in architecture and urban studies will be elaborated in the next chapter.

3.3 Part Three: Fractals; Geometry of Complexity

> 'This is a geometry of order on many scales, a geometry of organised complexity' (Batty and Longley, 1994, p.57).

As discussed in the previous part, the fractal property can be understood as one of the characteristics of complex systems, and therefore, can be identified as 'the image of chaos' or 'the geometry of complexity'. The theory of fractals has been developed in parallel to chaos and complexity theories, but not necessarily by scientists with the same background. For instance, while the meteorologist, Lorenz (1963), is one of the pioneers in studying chaos, the mathematician, Benoit Mandelbrot (1977), is well known for his discovery of fractals as the real geometry of the nature. This research attempts to explore the overlaps of these parallel studies to enhance a better understanding of complexity theory.

Fractal structures have existed in many real world areas, such as the weather, the stock market, the universe, clouds, etc. An increasing number of papers on fractals appears in journals, books, conference outcomes and so on. Scientists and researchers of different backgrounds, from pure or applied sciences to arts, hold seminars and conferences to share their findings on fractals. These attempts demonstrate that our knowledge of fractal theory is gradually improving and is by no means complete. What follows is a general review of the theory of fractals, explaining the main concepts behind fractal, as opposed to Euclidean, geometry. It then focuses on calculating fractal dimension as a mathematical means of measuring the level of physical complexity that a fractal object exhibits.

3.3.1 Fractal; Terminology, meaning and definition:

> A child draws a cloud, a smoothly rounded bulk, perhaps with wavy or scalloped edges. A child's tree is a green mass sits atop a brown trunk. As children or adults, we own a repertoire of such stylized form. Our mental lightning bolts are Z's; our volcanoes are inverted and decapitated cones; our rivers are lines. Nature's objects are not so simple... These are not what really exist in the nature. The rivers, the clouds, the snowflakes of our usual perceptual tool kits miss much of nature's complexity (Gleick, 1990, unpaginated).

One wintry afternoon in 1975, seeking an appropriate word for his discovery, the mathematician, Benoit Mandelbrot, came across a Latin word, the adjective *fractus,* from the verb *frangere,* which could be defined 'to break'. 'The resonance of the main English cognates – *fracture* and *fraction* – seemed appropriate'; therefore, 'Mandelbrot created the word (noun and adjective, English and French) *fractal'* (Gleick, 1987, p.98). The term also implies the meaning 'irregular and fragmented', which Mandelbrot found to be useful, describing the objects which seemed to us irregular in geometric terms. He showed that many of irregular and fragmented patterns around us in nature could be described by fractal geometry. It helps us to study those forms that Euclid leaves aside as being formless or morphologically amorphous. While we use classical geometry to communicate the designs of technological products and a first approximation of physical objects, fractal geometry describes the forms of natural creations. Therefore, it can be claimed that 'fractal geometry is an extension of classical geometry' (Barnsley, 1993, p.1).

Bhutta (1999) suggests that there are two important properties of fractals by which the term can be defined: self-similarity and fractional dimension. Based on the first property (self-similarity), a useful definition is provided by Feder (1988, p.11): 'a fractal is a shape made of parts similar to the whole in some way'. In another words there is self-similarity over different scales of a fractal object. However, based on the second property, 'fractal' can be defined as: 'Every set with a non-integer dimension is a fractal' (Mandelbrot, 1983, p.15). While our minds have become used to the conventional integer dimensions of Euclid over the last 2500 years, Mandelbrot suggests that most objects around us in nature exhibit non-integer dimensions, called fractal dimensions. The next section explains the notion of non-integer fractal dimension, as it is an essential part of understanding the theory and its applications.

3.3.2 Fractal Dimension

The term 'fractal dimension' indicates that there are fragmented or "non-integer" dimensions in nature, as opposed to the "integer" dimensions of Euclidean objects (one, two or three dimensions and so on). We all remember that 'the line has one dimension, length; the plane has two dimensions, length, and width; the cube has three dimensions, length, width, and height' (Cooper, 2000, p.40). Koch (1993) provides the following illustration (figure 3.14) to show the difference between integer and non-integer dimensions.

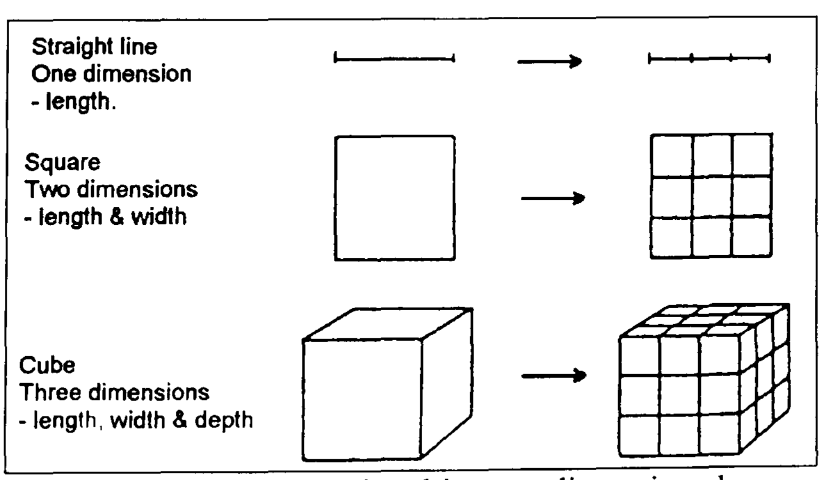

Figure 3.14: the conventional integer dimensions known as Euclidean dimensions (Koch, 1993, reproduced in Cooper, 2000, p.40)

As figure 3.14 shows, there is a logical scaling relationship between the whole size of a Euclidean shape and its subdivisions, by which mathematically one could find the dimension of an object. The following simple equation shows this relationship (Bovill, 1996, p.27):

$$D = \frac{\log N}{\log \frac{1}{S}} \quad \text{or;} \quad D = \log N \times (\log S^{-1})^{-1} \qquad \text{(Equation 3.4)}$$

The above equation reveals the power law relationship between the number of elements existing in different scale of an object; where D represents 'Dimension', N shows 'Number of elements' countable at a specific scale, S means the respective 'Scale' of an object. For example, to find a dimension (D value) of a square shape, we can divide a square into nine (N=9) equal smaller squares (as shown in figure 3.14) in which each smaller square is similar to the whole at the scale of one third (S=1/3). Placing the values of N and S in the equation, the result will be two (D=2) which implies that this shape is two-dimensional.

$$D = \frac{\log 9}{\log \frac{1}{1/3}} = \frac{\log 9}{\log 3} = 2 \qquad \text{(Equation 3.5)}$$

If we examine the square shape at other scales (1/4, 1/5, etc), the result will not change and remain at the integer dimension of two. If we repeat the calculation for a line shape and a cube shape, the equation shows the values of one and three for D (D=1, and D=3) respectively, which are again integer. However, in a fractal shape the result of calculating its dimension (D_f) will be usually non-integer. Figure 3.15 provides a classical example of fractal shape known as the 'Koch Curve'.

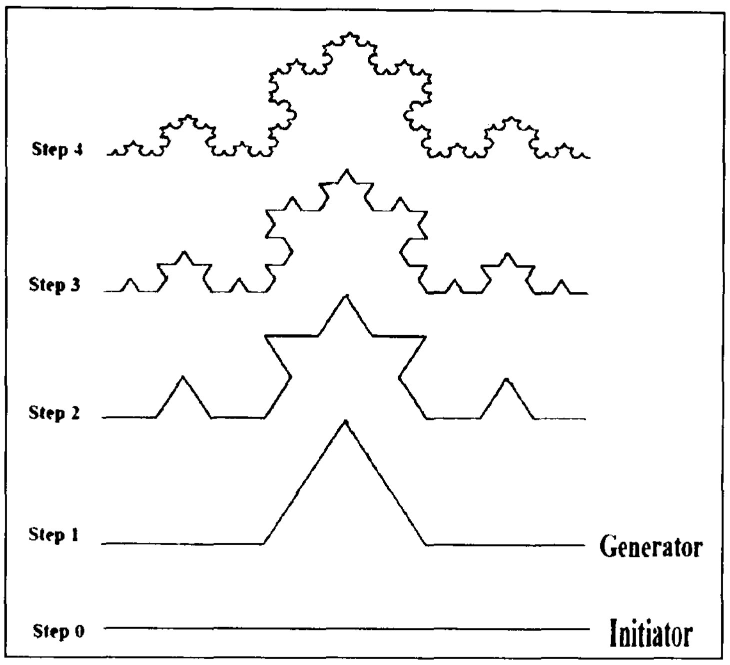

Figure 3.15: The Koch curve (Peitgen *et al*, 2004, p.89)

The Koch curve clearly manifests the property of self-similarity at its different sizes and scales. Any one-third part of the curve is similar to the whole image. The figure shows five levels of the shape's complexity. Comparing any two sequential levels reveals that the curve repeats itself 4 times (N=4) at any 1/3 section (S=3). According to Euclidean Law, any line has one dimension (*D*=1) irrespective to be straight or curvy. However, Mandelbrot (1983) argued that nearly all fractals represent higher dimensions ($D_f > D$) and, in the case of the Koch curve, $D_f = 1.26$. A non-integer fractal dimension such as the Koch curve can be calculated by equation 3.4 in the following way:

$$\frac{\log 4}{\log \frac{1}{1/3}} = \frac{\log 4}{\log 3} \approx 1.26 \qquad \text{(Equation 3.6)}$$

Fractal objects exhibit different dimensions as they unfold in the space. In the physical world, their dimensions may vary between $0 < D_f < 3$. For instance, fractals illustrated in figures 3.16, 3.17, and 3.18 represent the values of 0.6309, 1.8928, and 2.7268 respectively.

Figure 3.16 illustrates another classic example of a fractal known as the Cantor set (also called the Cantor dust). Mandelbrot saw the Cantor set as a model of the occurrence of errors in an electrical transmission line (Gleick, 1987). The paradoxical qualities of error and error-free periods in electronic transmissions were a concern of mathematicians in the 19th century. It is generated by repeatedly removing one-third from the centre of a line with one unit length. In other words, as Gleick (1987, P.93) instructed, 'Begin with a line; remove the middle third; then remove the middle third of the remaining segment; and so on' (figure 3.16).

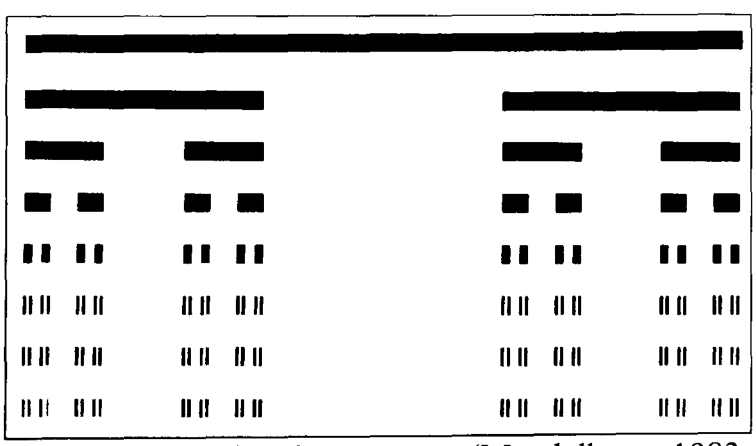

Figure 3.16: The Cantor set. (Mandelbrot, 1983, p.80)

In the Cantor set, at each one-third section (S=1/3), there are only two segments (N=2). Therefore, based on the logarithmic equation 3.4, its fractal dimension will be approximately 0.6309 (D_f).

$$D_f = \log 2/\log 3 \cong 0.6309 \qquad \text{(Equation 3.7)}$$

A few mathematicians in the early 20th century conceived monstrous-seeming objects made by the technique of infinitely adding or removing many parts. For instance, in 1916, Wraclaw Sierpinski (1882-1969) developed two abstract fractal shapes, the Sierpinski triangle, and Sierpinski carpet. Both are essentially flat, but have three-dimensional analogues (Mandelbrot, 1983). The Sierpinski carpet (figure 3.17, left), can be constructed 'by cutting the centre one-ninth of a square' (Gleick, 1987, p.101). Then the remaining parts will be equal to eight; again cutting out the centres of the eight smaller squares; and so on.

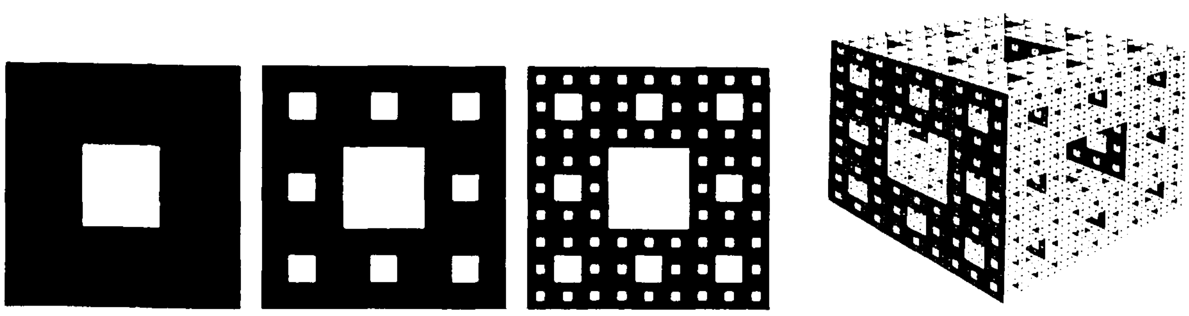

Figure 3.17: The three steps of generating the Sierpinski carpet (Left) and its three-dimensional analogue – called the Menger sponge. (Mandelbrot, 1983, pp.144-145)

Each of eight (N=8) is similar to the original square but one third smaller (s=1/3). Therefore, its fractal dimension will be 1.8928.

$$D_f = \log 8/\log 3 \cong 1.8928 \qquad \text{(Equation 3.8)}$$

The three-dimensional analogue of the Sierpinski carpet is called the Menger sponge (figure 3.17, right), a solid-looking lattice that has an infinite surface area, yet zero volume. The number of similar cubes at each level of its third scale (s=1/3) will be 20 (N=20), and therefore its approximate dimension is 2.7268.

$$D_f = \log 20/\log 3 \cong 2.7268 \qquad \text{(Equation 3.9)}$$

Figure 3.18 (left) illustrates the three steps of generating the Sierpinski triangle and its three-dimensional analogue. A triangle\pyramid is repeatedly divided into four congruent triangles and the centre triangle is removed. Therefore, in the case of Sierpinski triangle three (N=3) similar triangles will be the result at half-scaled level (S=1/2). Thus its fractal dimension is approximately 1.5849.

$$D_f = \log 3/\log 2 \cong 1.5849 \qquad \text{(Equation 3.10)}$$

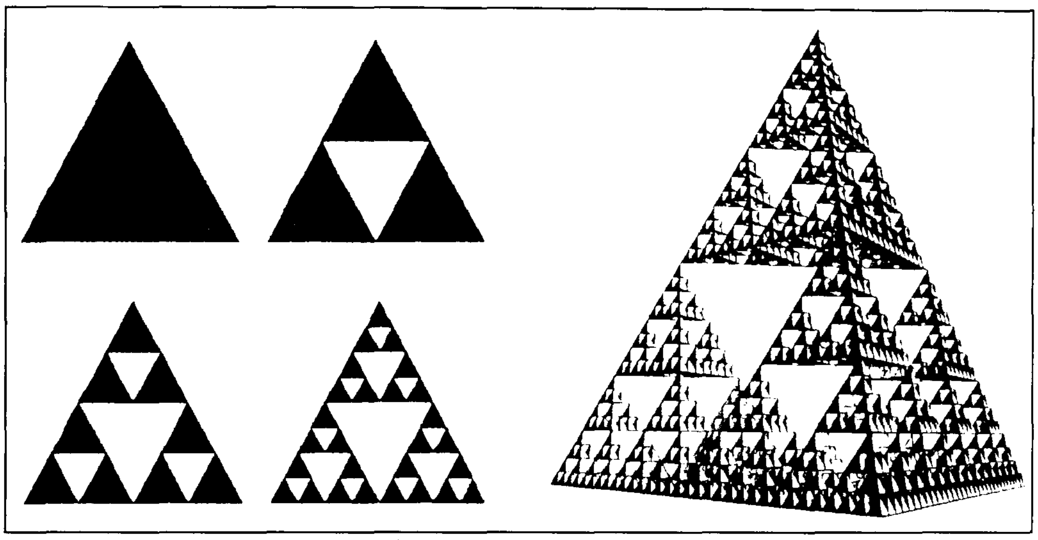

Figure 3.18: The Sierpinski triangle (Left) and its three-dimensional analogue (a fractal skewed web). (Mandelbrot, 1983, pp.142-143)

In some rare cases, a fractal object may have an integer dimension. For instance, the skewed web showed in figure 3.18 (right) is a fractal with the dimensional value of two ($D_f = 2$). It is the three-dimensional analogue of the Sierpinski triangle, but the number of similar pyramids at each level of its constructs is four (N=4) at any half-scaled levels (S=1/2), and therefore, according to the logarithmic equation, its fractal dimension is exactly two.

$$D_f = \log 4/\log 2 = 2 \qquad \text{(Equation 3.11)}$$

3.3.3 Types of Fractals

Fractal geometry involves identifying systems in which elements are repeated in a similar fashion from scale to scale (Batty and Longley, 1994). If this similarity is strong in a geometric sense, then it is referred to as *self-similarity* or in its weaker form as *self-affinity*. Fractals can be well typified by the degree of similarity or randomness that they exhibit in terms of *"linear self-similar fractals"* or *"nonlinear self-affine fractals"* (see also Mandelbrot, 1983, pp.166-167).

3.3.3.1 Linear fractals (Self-similar fractals):

Mandelbrot (1983, p.166) suggested that the study of 'fractal geometry must begin by dealing with the fractal counterparts of straight lines... called linear fractals'. He defined them as 'fully invariant under similitude or, at least, nearly self-similar'. According to Gleick (1988, pp.21-22), linear fractals are classical fractals and 'if you look at a very small part of a fractal's overall shape; it looks exactly like the original fractal, only smaller'. These types of fractals can be constructed mathematically through some simple rules defined by one or more equations. That is why they are also called mathematical fractals. Cooper (2000, p.41) writes that 'mathematical fractals are mathematical constructs, objects formed by the repetition of a simple geometric instruction'.

The Koch curve, Cantor set, Sierpinski carpet, and the Menger sponge – described earlier as classical fractals – are examples of linear fractals. The Koch snowflake is also another example of this type, which can be constructed by arraying of three Koch curves around a triangle (figure 3.19). To construct it, '...begin with sides of length 1. At middle of each part, add a new triangle one-third the size; and so on' (Gleick, 1987, p.99). The repetition of this simple rule creates an amazing structure similar to a snowflake. An interesting thing about a fractal shape is that the boundary length is infinite. In the case of the Koch snowflake, the length of its boundary is 3 x 4/3 x 4/3 x 4/3...- infinity. Yet its area remains less than the area of a circle drawn around the original triangle. Thus, an infinitely long line surrounds a finite area (Gleick, 1987).

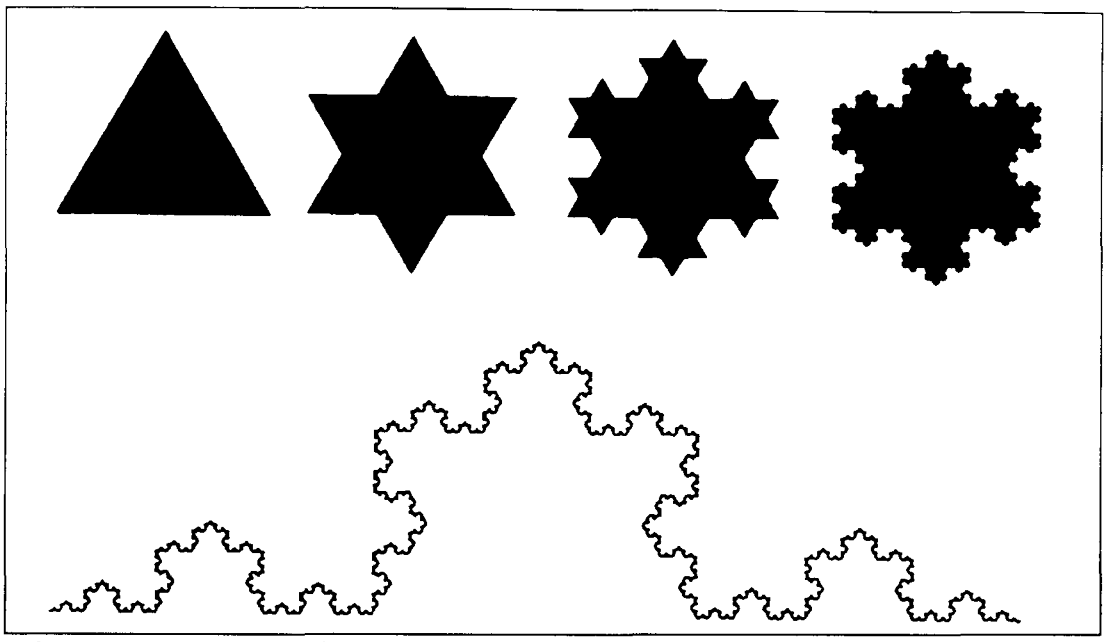

Figure 3.19: The Koch snowflake (above), which is the triangular version of the Koch curve (below). (Gleick, 1987, p.99)

3.3.3.2 Nonlinear Fractals (Self-affine fractals):

It might be argued that fractals are fully invariant under the notion of self-similarity. However, according to Mandelbrot (1983, p. 166), 'such is emphatically not the case'. In some cases, varying regions of a fractal object appear as twisted or skewed scale copies of the original, while still other regions have shapes that bear no resemblance to the original. In fact, 'objects which are stretched or distorted and scaled in the manner of fractals at successive scales are still fractals in our use of the term, although their scaling is said to embrace the property of self-affinity rather than self-similarity' (Batty and Longley, 1994, p.63). Therefore, they are called self-affine fractals. As Wahl *et al* (1998, pp.22-23) explain, 'the overall appearance of a nonlinear fractal closely resembles some of its smaller parts, but always with some variation'.

Since the shape of this type of fractals is generated by a nonlinear transformation, they are also called nonlinear fractals. In a linear fractal, the calculated fractal dimension remains constant at all scale levels, while it varies in a nonlinear one. In fact, the randomness is part of the formation process of this type, which creates this variation (Wahl, 1998). That is why the fractal dimensions exhibited by different parts of a nonlinear fractal are usually varied. Random fractals, 'natural, stochastic, or statistical fractals' are the other names given to this type of fractals (Cooper, 2000, p.41).

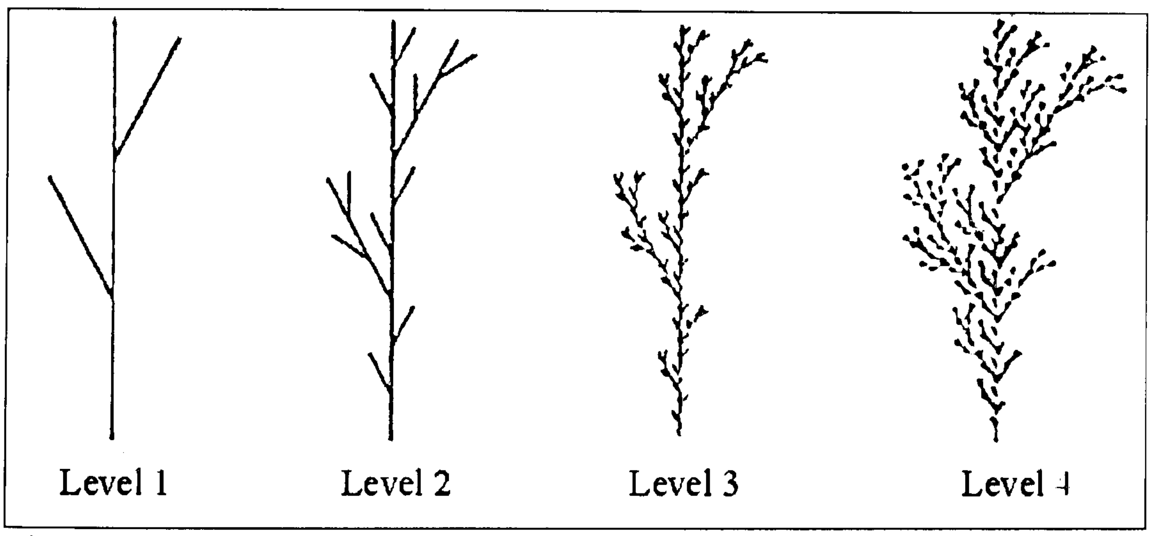

Figure 3.20: Bifurcation in a bush as an example of natural fractals. (Lorenz, 2003, unpaginated)

Nonlinear fractals can be divided into two groups: mathematical fractals and natural fractals. Many nonlinear fractals look organic – as can be seen in biological forms (e.g. human lungs) or in many other organically shaped phenomena in nature. Bifurcation in a bush displays the self-similar characteristics of a natural fractal object (figure 3.20). The whole tree displays irregularity in Euclidean terms but made up smaller similar versions of it as you zoom in on any branches. These branches are themselves made up of smaller similar versions but, in fact, are not exactly the same.

Today, many of the fractal phenomena in nature can be mathematically constructed through advanced computer simulation techniques. Mathematicians and experts in computer simulations have succeeded in modelling the self-similarity existing in nonlinear natural fractals through simple mathematical equations (e.g. Wahl *et al*, 1998; Russ,1994). As nonlinear fractals are derived from the equations that do not produce straight-line segments, in order to generate them, one must specify a generator and diverse other rules (Mandelbrot, 1983). The Mandelbrot set and Julia sets are the classical examples of mathematically generated fractals (figure 3.21). According to Cooper (2000, p.43), 'in mathematical fractals, this self-similarity can be repeated over an infinite number of scales, while in natural fractals it is repeated over a limited number of scales'. In the case of the bush, for example, its self-similarity is only four levels deep.

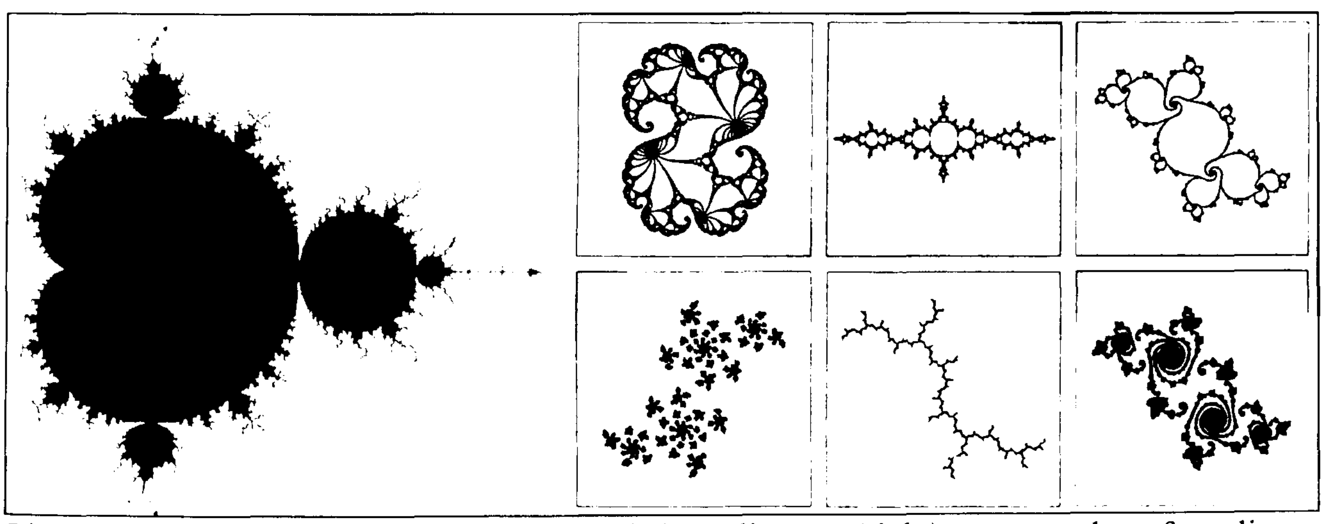

Figure 3.21: The Mandelbrot set (left), and the Julia sets (right) as examples of nonlinear mathematically generated fractals. (Left, Mandelbrot, 1983, p.188; Right, Gleick, 1987, p.222)

'A set of converging points of a plane when tested with the equation $Z = Z^2 + C$ (equation 3.5), creates the Julia sets with varying Z values (figure 3.21, right) (Wahl *et al*, 1998). The Julia sets are calculated by iteration with a programme that repeated the feedback loop (Gleick, 1987). To iterate them, an initial value is selected and will be applied to a fixed operation repeatedly, until some desired patterns are obtained. Different patterns usually appear through the equation 3.5. The resulting patterns either 'converge to a certain point or grow without bound escaping to infinity' (Wahl *et al*, 1998, p.111).

In 1979, Mandelbrot discovered that he could create an image (the Mandelbrot set) in the complex plane that would serve as a catalogue of all Julia sets (figure 3.21, left). To iterate the Mandelbrot set, a constant Z value with varying C values is tested through the equation 3.5. To test a point, take an initial number (Z); square it (Z^2); add the original number (C); square the result; add the original number; square the result and so on. 'If the total runs away to infinity, then the point is not in the set. If the total remains finite (it could be trapped in some repeating loop, or it could wander chaotically), then the point is in the set' (Gleick, 1987, p.224; for more detailed explanation see also Mandelbrot, 2004).

By repeating the above procedure, 'the Mandelbrot set emerges'. In Mandelbrot's first crude computer printouts, a rough structure appeared. As the quality of computation improved, he could gain more detail. Interestingly, the resultant pattern in the Mandelbrot set is the index of all Julia sets in which 'each point on the Mandelbrot set corresponding to an individual Julia set' (Wahl *et al*, 1998, p.121).

3.3.4 Fractal generators

The fact, which should be emphasized again, is that fractal objects usually originate from very simple shapes at the initial level of their hierarchical structures by which their formation at different levels is determined. These simple shapes are called '*generators*' (Mandelbrot, 1983). We can easily find the generators of the previous examples given for linear fractals (e.g. see the level one in figure 3.20 or the step one in figure 3.15). However, when there are random orientations in the structure of a fractal object (in the nonlinear type), it might be a little more difficult to perceive the self-similarity at a glance and recognize its pattern generator (e.g. in Julia and Mandelbrot sets).

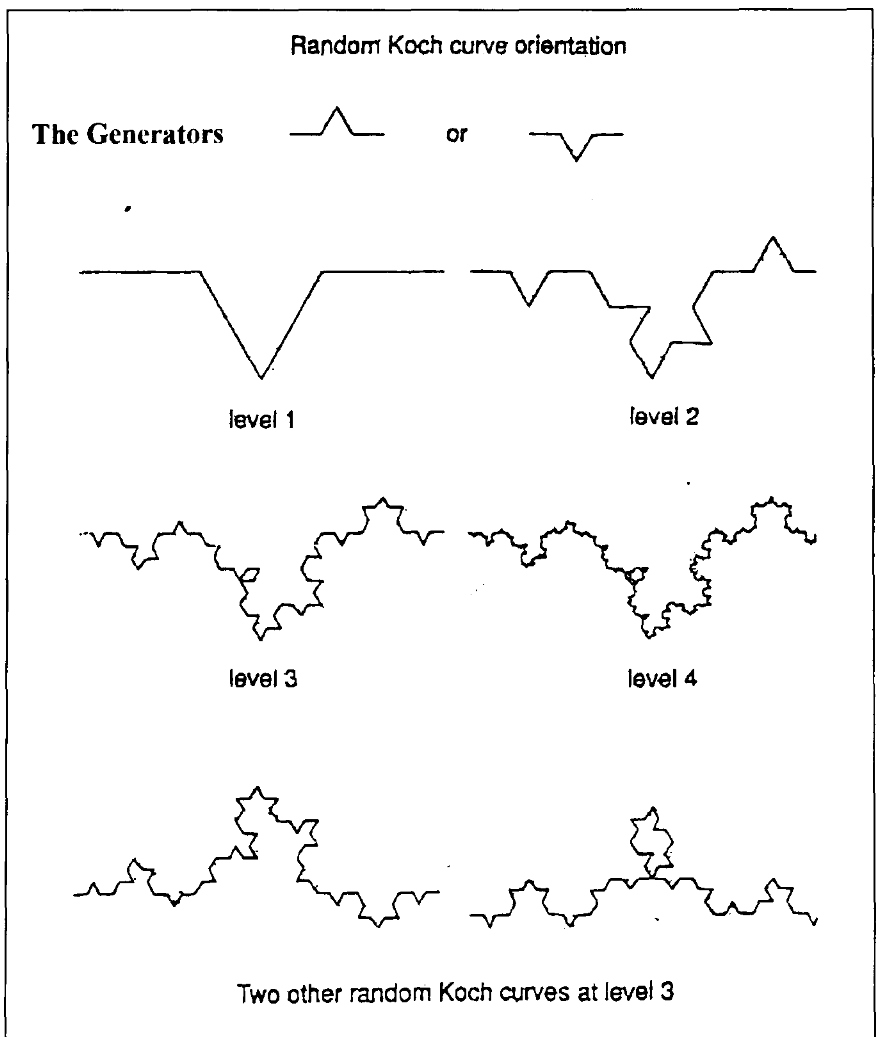

Figure 3.22: Random Koch curves created through random selection of two simple generators. (Wahl *et al*, 1998, p.143)

In some nonlinear fractals, there may be more than one generator allowing random orientations in the process of generating them. Random distribution of one or more fractal generators can turn even a linear fractal to nonlinear one. Wahl *et al* (1998, p.143) illustrate an experiment of this with a Koch curve (figure 3.22).

Coastlines are the popular examples of randomly generated fractals. Mandelbrot (1983, pp.210-245) illustrated some mathematically constructed coastlines and islands with random walk generators (figure 3.23). Their shapes are similar to the random Koch curves. It can be claimed that the random Koch curve 'has much of the complexity which we would see in a natural coastline - folds within folds within folds, and so on' (Peitgen *et al*, 2004, p.88). Therefore, the boundary length of a coastline – as that was seen earlier in the Koch snowflake (figure 3.19) - is infinite, while the area bounded by the coastline remains finite. Mandelbrot (1983, p.25) stated that 'coastline length turns out to be an elusive notion that slips between the fingers of one who want to grasp it.'

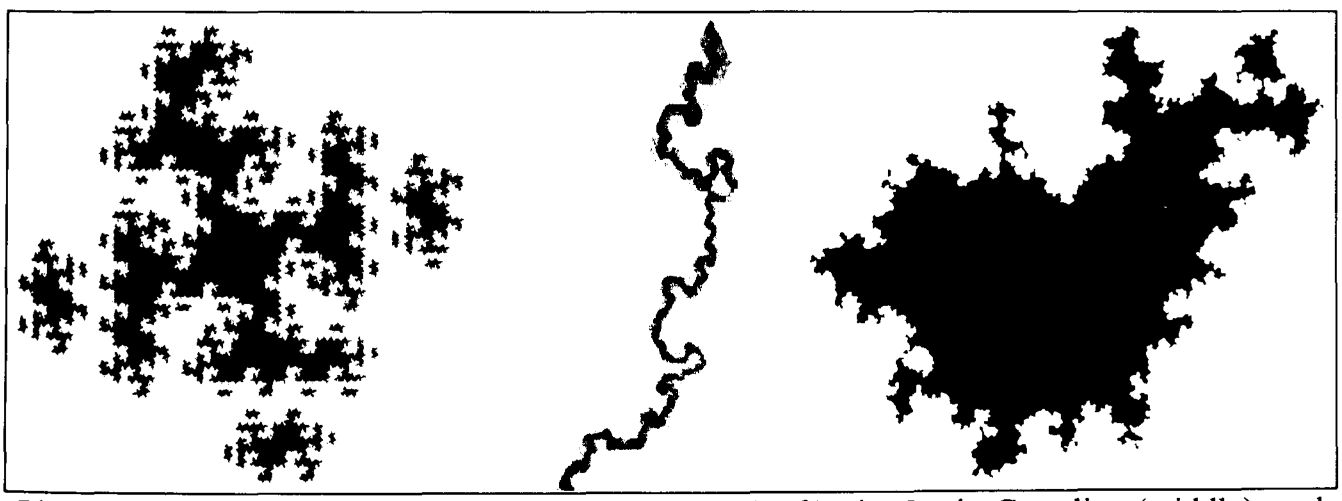

Figure 3.23: Random coastlines. The Squig Curve (Left), the Squig Coastline (middle), and the Squig Island. (Mandelbrot, 1983, pp.228-230)

The reason for such an elusiveness lies in the fact that more and more details appear as one observes a fractal phenomenon from closer and closer distances. For instance, looking down on the coastline of Britain from a great distance one cannot see all the small inlets which will come up in a closer observation – for example when walking along the beach. Therefore, measuring the length of the coast of Britain becomes varied at the various scales (see figure 3.24, section 3.3.5.1).

The boundaries of cities are similar to the outlines of the coasts – e.g. the changeover from the city to the natural environment, from high-density built-up areas to low-density areas, from regions of dwelling houses to regions of one-family houses, and so on (Lorenz, 2003). Hence, if one wishes to compare different fractal boundaries from the viewpoint of their extent, 'length is an inadequate concept' (Mandelbrot, 1983, p.25). Instead of the length, measuring the fractal dimension suggests a more valid base for such a comparison.

3.3.5 Methods for measuring fractal dimension

There are several methods for calculating the fractal dimension(s) of a complex shape. Based on the type of the shape or structure we are dealing with (nodes, lines, boundaries, curves, surfaces, spaces, etc), one or more of the following five methods might be appropriate:

1. Box Counting method (grid dimension)
2. Structured Walk method (ruler dimension)
3. Perimeter-Area method
4. Information dimension method
5. Mass dimension method

All of the above methods follow the same principle built on the logarithmic equation 3.4 and seek to formulate a power law relationship between the size (e.g. length, area, volume) and the various scales at which the fractal dimension of an object is measured. Among these methods, Box Counting and Structured Walk methods have wide applicability in measuring fractal dimensions of urban forms including urban patterns and city boundaries, which are the focus of this research at the empirical stage. An explanation for these two methods is given below (see appendix B for a brief explanation of other methods).

3.3.5.1 Box counting method (grid dimension):

The box dimension is defined as the exponent D_b in the following relationship:

$$N(d) \approx \frac{1}{d^{Db}} \quad \text{or} \quad D_b = \log N_d \times \log \frac{1}{d} \qquad \text{(Equation 3.12)}$$

In equation 3.12, N(d) is the number of boxes of linear size d necessary to cover a data set of points distributed in a two-dimensional plane. The basis of this method is that, a number of boxes proportional to 1/d are considered to cover a set of points lying on a smooth line, and proportional to $1/d^2$ to cover a set of points evenly distributed on a plane, and so on.

This dimension is sometimes called the grid dimension, because for mathematical convenience, the boxes are usually part of a grid. It is obviously a very difficult computational problem to find the configuration that minimizes N(d) among all the possible ways to cover the set with boxes of size d. Instead, one could define a box dimension where the grid is placed at any position and orientation, to minimize the number of boxes needed to cover the set.

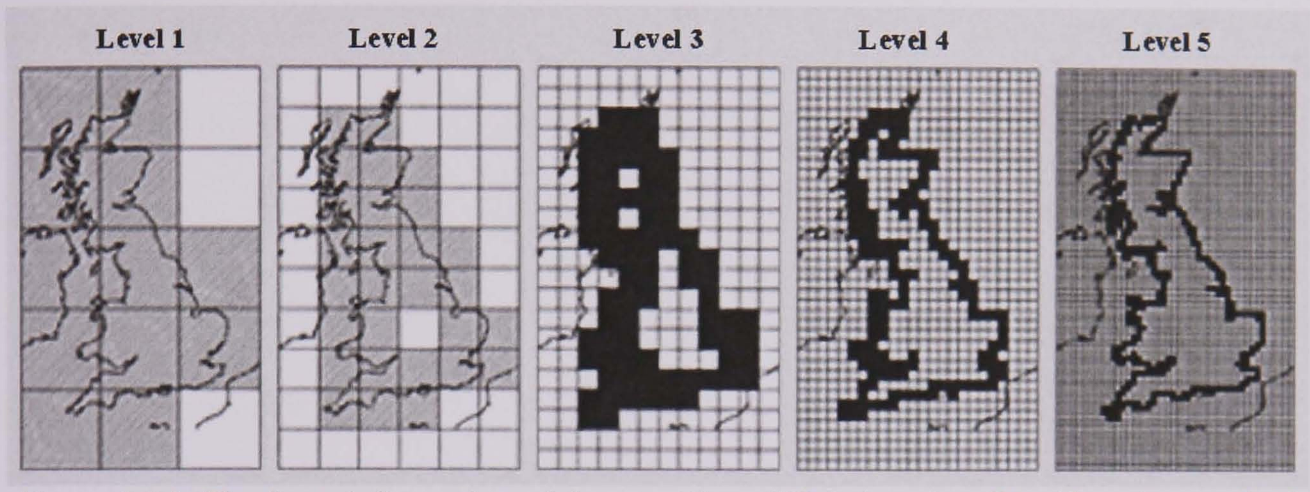

Figure 3.24: The fractal dimension of the coastline of Britain using Box Counting method (Lorenz, 2003, unpaginated)

In practice, D_b can be measured using various map scales or varying the box sizes (d values) while the scale of the map is maintained. To obtain points that are evenly spaced in log-log space, it is best to choose box sizes d that follow a geometric progression (e.g. d = 1, 3, 6, 12,...), rather than use an arithmetic progression (e.g. d = 1, 2, 3, 4,...). For example, the Box Counting dimension of the coastline of Britain (figure 3.24) can be measured using varied sizes for d (1/3d, 1/6d, 1/12d…) as reflected in table 3.2. The average of the dimensions calculated for five levels of scale will be 1.241.

level	unity size "1/d"		log 1/d	"N" pieces		log(N)	Box dimension	
1	d(1)=	1/3	0.477	N(1)=	12	1.079	D_b	
2	d(2)=	1/6	0.778	N(2)=	28	1.447	D(d1-d2)=	1.222
3	d(3)=	1/12	1.079	N(3)=	77	1.886	D(d2-d3)=	1.459
4	d(4)=	1/24	1.380	N(4)=	157	2.196	D(d3-d4)=	1.028
5	d(5)=	1/48	1.681	N(5)=	374	2.573	D(d4-d5)=	1.252
							D_b (slope)=	1.241

Table 3.2: The fractal dimension measured for the coastline of Britain using the Box Counting method. (Lorenz, 2003, unpaginated)

Graphically, the Box Counting dimension can also be calculated by transforming the result in the table 3.2 to a log-log graph. As shown in figure 3.25, the number of boxes (N_d) of linear size d, necessary to cover the whole boundary of Britain d, are counted; and the logarithm of N_d (on the vertical axis versus, is plotted against the logarithm of 1/d (on the horizontal axis). The slope of the resulting line of the logarithmic graph is the fractal dimension of the image.

In the most cases, the result is not a straight line. Only in a linear fractal with absolute self-similarity (e.g. the Koch curve, figure 3.19) in which the calculated fractal dimensions remain stable, the resultant line is straight. In a self-affine fractal (e.g. the random Koch curves, figures 3.22 and 3.24), the gradient of the line is varied at different examined scales. However, a replacement-line can be calculated for the latter (figure 3.25, right), which runs straight to represent the average of the dimensions measured at different scales.

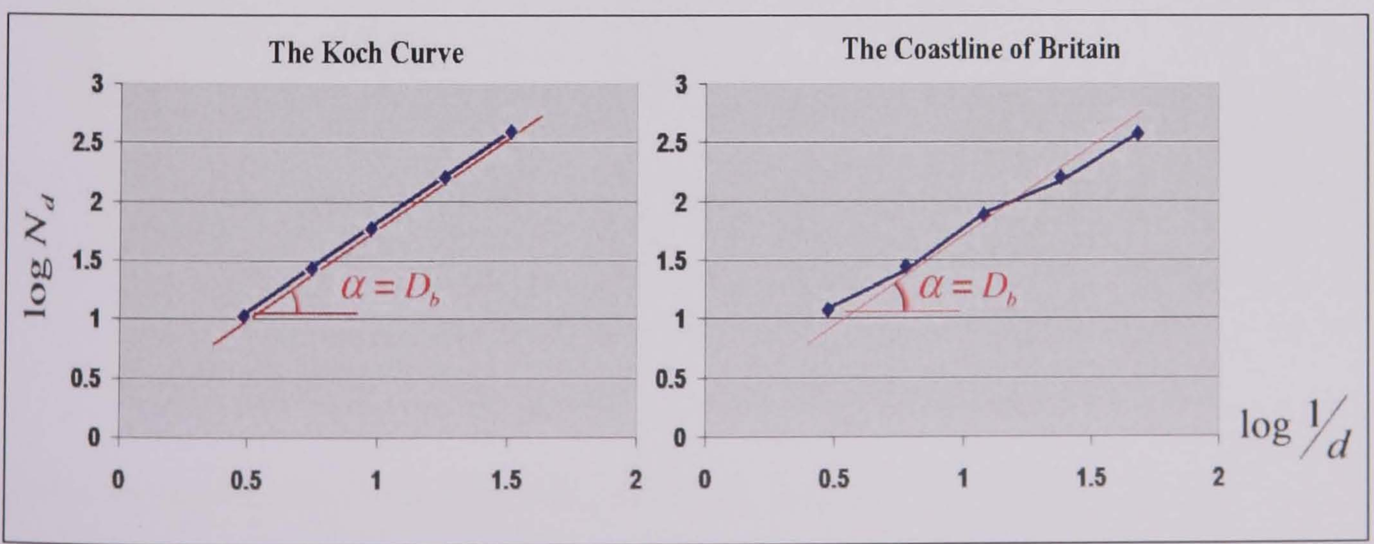

Figure 3.25: The gradient of the line in the log-log graphs indicates the fractal dimensions assessed at different scales. The gradient of a self-similar fractal (the Koch curve, left) is constant, while of a self –affine fractal (the coastline of Britain, right) is varied.

3.3.5.2 Structured walk method (ruler dimension):

The Structured Walk is another method of estimating the fractal dimension of a jagged, self-similar line such as a coastline, a mountain ridge, or a city border. This method is also called ruler dimension (D_r) defined through the following equation, where N(d) is the number of steps taken by walking a divider (ruler) of length d on the line.

$$N(d) \approx d^{-D_r} \quad \text{or,} \quad D_r = \log N_d \times \log \frac{1}{d} \quad \text{(Equation 3.13)}$$

In practice, to obtain Dr one counts the number of steps N(d) taken by walking a divider (ruler) of length d on the line, and plot the logarithm of N(d) versus the logarithm of d. It should be noted that in general, a ruler of length d will not cover exactly the line, but we will be left with a remainder.

Figure 3.26: The fractal dimension of the coastline of Britain using the Structured Walk method (Lorenz, 2003, unpaginated)

Referring again to the coast of Britain, the perimeter can be replaced by different polygons (figure 3.26). The first one (level 1) is a polygon with seven 300 km straight-line segments which amount to a total length of 2289 km (the length of each segment equals to the radius of each circle drawn in figure 3.26). This total length of the polygon increases by 232 km if the single polygon-line is reduced to 200 km (level 2). In the same way, 165 pieces of 25 km polygon-line are required to close the coastline, which enlarge the total length to 4120 (level 5). Therefore, the measured length of the polygons replacing the coastline increases when the scale, length of segments of polygons, becomes smaller. Table 3.3 shows the result of fractal dimensions measured with different walk-dividers using equation 3.13.

level	unit length "d" (km)		1/d	Number of segments "N"		Length (km)	Ruler dimension	
1	d(1)=	300	1/300	N(1)=	7.63	2289	D_r	
2	d(2)=	200	1/200	N(2)=	12.6	2521	D(d1-d2)=	1.239
3	d(3)=	100	1/100	N(3)=	29.1	2906	D(d2-d3)=	1.205
4	d(4)=	50	1/50	N(4)=	67.1	3360	D(d3-d4)=	1.209
5	d(5)=	25	1/25	N(5)=	165	4120	D(d4-d5)=	1.291
							D_r (slope)=	1.231

Table 3.3: The fractal dimension measured for the coastline of Britain using the Structured Walk method. (Lorenz, 2003, unpaginated)

Lorenz (2003) writes that as the straight-line segments are getting smaller and smaller, the polygon representing the coastline of Britain more and more approaches its shape as can be seen in the real world. It also means that the exactness of a map of Britain depends on the scale of the map and limits to the size of the single straight-line segments used to draw that map. The replacement polygons are similar to the iterations of mathematical fractals, where the fractal curve is getting longer and longer from one iteration step to the next (e.g. the iteration steps creating the Koch curve, figure 3.15).

3.3.6 Fractals in everyday life

> What is the information content of a picture? Measures, pictures, dreams, chaos, flowers – the hours of the days keep rushing by; do not let the beauty of all these things pass by too (Barnsley, 1993, unpaginated).

The advice given by Barnsley (1993) for a desired daily experience can be interpreted as a recommendation to see fractals in our environment. He suggests that fractal dimension, as the density of occupation, gives an indication of the liveliness of a space. Crompton (2001, 2006) expands this further and shows what happens if we explore our everyday environment and perceive it fractally. He suggested that 'if the size of a space is measured by counting the number of places available for particular activity, rather than using an absolute measure such as the square metre, then small people may find the world larger' (Crompton, 2001, p.243).

Crompton compared the result through the power law logarithmic relationship (Equation 3.4) to measure the fractal dimension of a space. He concluded that we might perceive the space as larger when we were younger. In other words, 'the subjective size, to a certain extent, is independent of its area in square metres' (Crompton, 2001, p.253). Furthermore, Crompton (2001, pp.253-254) suggests that designers can create a usable space from nothing – that appears larger even for adults – by increasing the fractal dimension of space rather than increasing its metric size.

Crompton (2006) has also found that our familiarity with a place influences our mental estimation of a walking distance, which is in fact another indication that our everyday experience of environment is fractal. He observed that estimates of walking distances up to 2 miles along a busy road were correlated with the length of time, between 2 and 26 months, that participants had been acquainted with the route in question. It was discovered that perceived distances increased the longer participants had known them.

Cooper (2000, 2003, 2007) carried out a series of projects to find linkages between fractals and the urban environment at street level. He believes that ‘fractal analysis of street vistas by calculating their fractal dimension assist us to gauge levels of visual variety [physical complexity] present in everyday streets’ (Cooper, 2007, p.13). To validate the result, Cooper carried out a subjective in parallel to physical fractal survey, which led him to assess the homogeneity of visual variety perception.

The above evidence implies that there is something in common between constructs in nature and the biological constructs of our mind, which encourage us to call them beauty. Mikiten *et al* (2000, unpaginated) claimed that ‘the brain is known to be a structured system of hierarchically-organized modules…, [and] the modules contain within them yet other sub-modules which communicate among themselves. This pattern is repeated at several different levels of scale, culminating in what is a molecular and biochemical fractal of interacting and communicating systems. In a similar way, we can conceive of the mind as consisting of self-similar complexes of hierarchically arranged modules linked together in a way that can be expressed according to some algorithms’. They concluded that the systems of organization that characterize both mind and brain are at least partially fractal in nature.

According to a conversation between Salingaros and Padrón (2000, unpaginated), ‘We are affected by what we see. Our environment affects us, and this may well be why our mind is fractal, because our environment is fractal. Human beings have been surrounded by fractal structures for millions of years. A great deal of our mind's structure comes from this ancient relationship. It is only recently that we are surrounded by structures that are not fractal'. There is no other experience better than realizing that something that has happened in our mind exactly corresponds to something that happens in nature (Donahue, 1999). Cooper (2000, p.41) writes that 'it resonates to the way Mandelbrot believes nature organizes itself, that is also believed to be the way in which human perceive the world'. The view that our mind responds to a degree of complexity is perhaps best summed up in the following statement by German physicist Gert Eilenberger:

> 'Why is it that the silhouette of a storm bent leafless tree against and evening sky in winter is perceived as beautiful...The answer seems to me, even if somewhat speculative, to follow from the new insights into dynamical systems. Our feeling for beauty is inspired by the harmonious arrangement of order and disorder as it occurs in natural objects – in clouds, trees, mountain ranges, or snow crystals. The shapes of all these are dynamical systems jelled into physical forms, and particular combinations of order and disorder are typical of them' (Cooper, 2000, p.41; also quoted in Gleick, 1987, p.117).

3.4 Chapter Summary

According to the first stage of the research methodology (Chapter One, section 1.3.2.1), the literature review aims to highlight the advantages of fractal concept as compared to the conventional Euclidean approaches towards urban pattern and form (aim a and b). This review provides a theoretical backbone for the empirical sections in the following chapters, where the applicability of the proposed fractal analysis method is examined (aim c). Chapter Two highlighted the failures of Euclidean principles in morphological analysis, suggesting that new theories are required that can deal with the complex nature of urban evolution. For this purpose, Chapter Three attempted firstly to define the terms chaos, fractals, and the key vocabularies of complexity theory. Secondly, the relationship between fractals, chaos, and complexity was discussed. Thirdly, the differences between the mechanical and organic universe were highlighted to reveal the main concept behind complexity by which the theory might be better understood. More importantly, the characteristics of complex systems and their analogies with an urban system were identified to establish reasons why a city system should be viewed, studied, and treated as a self-organising complex system. In the last part (Part Three), the chapter focused on the geometry of complexity – fractals. The notion of non-integer fractal dimensions was explained to reveal its potential to analyse the organic forms, which is more accurate than integer dimensions known in Euclidian geometry.

In short, it can be concluded that both chaos and fractal theories are to be understood as subsets of complexity theory. While chaos theory explains the strange behaviour of the elements and components, which interact within a nonlinear complex system, fractal theory provides an explanation of the complexity emerging in the form and structure of such a system (see section 3.2.2.12). Complexity theory and fractals have a wide applicability to many natural and artificial systems whose dynamics – the interactions of local agents – generate highly ordered global patterns. These theories explain the evolutionary dynamics of systems whose temporal and spatial "fingerprints" or "morphological signatures" are fractal. As cities exhibit the characteristics of complex systems, they are good candidates for the application of complexity and fractal theories, which is the subject of the next chapter.

CHAPTER FOUR

THE APPLICATION OF COMPLEXITY THEORY AND FRACTALS IN ARCHITECTURE, URBAN DESIGN, AND PLANNING

Introduction:

The application of complexity theory in architecture, urban planning and design is essentially interdisciplinary (Wilson, 2000). Its foundation is in the both physical and social sciences. These sciences deal with a range of approaches from large contextual to small elemental scales including physical geography, human geography, social sciences, planning, real estate, urban design, landscape design, and architecture (Cooper, 2000). Researchers in each field have simultaneously explored the idea of complexity from their own viewpoints and made tremendous progress in the last 35 years. Each reinforces the others and improves our understanding of the city. However, the integration of such wide approaches in one comprehensive theory is difficult, if not impossible. This may seem problematic, and as Wilson (2000) states: different perspectives have not been forced together to create an adequately articulated body of theory.

Nevertheless, there is an increasing number of papers and projects developing the theory of complexity, claiming to be a firmer foundation for the critical ideas that relate the theory to the evolution of cities. In fact, the more we understand how complex systems behave, the more we find them applicable in the study of cities. Rosser (1994) and Cooper (2000) undertook a survey of contemporary research that sought to explain the developments that have been made in linking the theories of complexity and fractals to the field of urban science (table 4.1).

Macro Regional Scales	**Urban Geography**	Geomorphology	Malanson, Butler and Walsh (1990), Culling (1985)
		Glacial action	Oerlemans (1981)
		Patterned ground	Vitek and Tarquin (1984), Ray (1983), Gleason 1986), Lorenz (2003*)
		Rainfall dynamics	Rodrigues Iturbe (1989)
		Terrain analysis and modelling	Batty (1992), Musgrave (1992)
		Avalanche study	Butler and Walsh (1990)
		Subsurface convection cells	Kellog and Turncote (1990)
		Models of forest communities	Hudson *et al* (1988)
		Multi fractal analysis of topography	Lavallee Lovejoy, Schetzer, and Ladoy (1992)
		Fractal analysis of geologic time series	Plotnick and Pretergaard (1992)
		Fractal analysis of geography, channel, and river networks	Goodchild and Klinkenberg (1992), Phillips, Barbera and Roso (1992), Batty (1992), Veltri (2004*)
		Fractal analysis of Urban growth Fractal urban structure Land use pattern Scaling behaviour, size, shape and density distribution	Batty (1991, 1992, 1995, 2005*), Batty and Longley (1994a and 1994b), Batty Longley, Mesev and Xie (1995), Batty and Xie (1994), Batty, Steadman, and Xie (2004), Makse Havlin and Stanley (1995), White and Engelen (1994), Wieldlich (1994*), Peterson (1996), Klinger and Salingaros (2000*), Benguigui (2001*), Chen and Zhou (2003*, 2004*), Ikuo and Masanori (2003*), Rui and Penn (2004*), Salingaros (1999*, 2003*, 2005*), Lorenz (2003*), Matsuba (2003*), Yanguang and Yixing (2004*)
		Simulation techniques and urban Modelling (e.g. CA, DLA, CAST, Cristal city, and SIMCity for real)	Tobler (1979), Witten and Sanders (1981*, 1983*), Coucelis (1985, 1988, 1989), Phipps (1989), Cecchini and Viola (1990, 1992), Batty and Xie (1994), Xie (1994), Langlois and Phipps (1995*), Rasmussen and White (2002*), Liu and Andersson (2003*), Batty (2005*, 2007*, 2008*), Melin and Castillo (2002*), Martin *et al* (2008*), Jankovic *et al* (2005*), Silva and Clarke (2005*), Clarke and Birkin (2008*)
		Fractal analysis of aerial photography, GIS, and satellite imagery	Longley (1995*, 1996*, ,1997*, 2001*, 2003*), Nelilis and Briggs (1989), Lam (1990), De Cola (1994), Batty *et all* (1995), Shiode (1998*)
City Scales		Surface analysis	Broscoe (1992), Batty, Longley, Mesev and Xie (1995), Yfantis, Gallitano and Flatman (1992)
		Weather system	Lorenz (1960)
	Human Geography	Rank size and hierarchy formation	Beaumont *et al* (1981), Dendrinos (1985), Wong and Fotheringham (1990), Rosser (1994), Haag (1994), Wiedlich (1994), Allen *et al* (1978), Camagni *et al* (1986), Hakken (1977), Beckman and Puu (1985), Puu (1987,1993), Dendrinos (1994), Batty *et al* (1989), White and Engelen (1994)
		City as a self-organization system	Hakken (1977), Portugali (2000*),

City Scales			Salingaros (1999*, 2003*, 2005*)
		Central place theory	Arlinghaus (1985, 1992)
		Railways networks	Benguigui and Daoud (1991)
		Systems theory	Motloch and Woodfin (1993)
	Social Science	Predictability	Loye (1995), Loye and Eisler (1987), Portugali (2000*), Batty (1980*)
		Conceptual application	Deneke (1989), Feber and Koppelaar (1995), Byrne (1998*, 2001*), Melin and Castillo (2002*)
		Economics	Allen *et al* (1978), Camani *et al* (1986), Baumol and Benhabib (1989), Zhang (1991, 1994), Cilliers (1998*), Durlauf (2005*)
		Arms races	Saperstien (1984), Grassmal and Mayer-Kress (1989)
	Planning	Dynamic complex systems planning	Jacobs (1961*), Cartwright (1984), Wilson (2000*), Byrne (2003*, 2005*), Hamdi (2004*), Shane (2005*), Chettiparamb (2006*), Mashhoudi (2007*), Batty (2006*, 2007*, 2008*), Briassoulis (2008*), Marshall (2009*)
		Fractal analysis of street network and urban traffic structure	Thibault and Marchand (1987), Frankhauser (1998*, 1997*, 1994), Mizuno and Kakei (1990), Saligaros (1997), Jiang, Xiao-yan, and Qing-sheng (2002*)
	Urban Design	L-system as means of design and using fractal to indicate character	Robertson (1992, 1995)
		Fractal assessment and evaluation of urban elements	Cooper (2000*, 2003*, 2005*, 2008*), Haghani (2004*, 2006*)
		Fractal analysis of skylines	Oku (1990), Kamei (1992*), Cooper (2000*), Stamps (2002*)
		Complexity and Conceptuality of urban Design	Alexander (1977*, 1987*, 2002*, 2004*)
City Micro Scales (local)	**Architecture**	Complexity as a style	Jencks (1997, 2002*), Kavannagh (1992), Smith (1990), Salingaros (1999*, 2000, 2005*), Lorenz (2003*)
		Fractal evaluation of building facades	Bechhoefer and Bovill (1995), Bovill (1996), Trivedi (1989)
		Computerized fractal Architecture	Hanna (2002*), Jeffery (2004*), Crompton (2001*, 2002*, 2006*)
		Architecture and Complexity	Kavannagh (1992*), Jencks (1997, 2002*), Alexander (2002*, 2004*), Joye (2007*)
	Landscape Architecture	Fractal analysis and simulation of plants	Prusinkiewics and Lindenmeyer (1990)
		Fractal analysis and landscape preference	Milne and Wiens (1989), Milne (1991), Gotou, Sakuragi and Iwakuma (2002*), Hagerhall, Purcell, and Taylor (2004*)
		Complexity and fractal geometry as a style	Motloch and Woodfin (1993), Thwaites (1996), Jenks (2005*)

Table 4.1: A summary of applications of complexity, chaos and fractal theories in different scales of urban studies from city regional to architectural scales. (Derived from Rosser, 1994, p.553; Cooper, 2000, p.215; updated by the author, 2008 – the updated entries marked with asterisks)

The number of publications in related fields is an indication of the broad range of approaches, which itself supports the belief that fractals and complexity are universal theories, and particularly, shows their tremendous potential in the better understanding of the city system. The dates of the published papers (cited in table 4.1) reveals the trend to link cities and the new theories of complexity, chaos, and fractals to be increasing year by year during the last 4 decades. This reflected in the following pie chart:

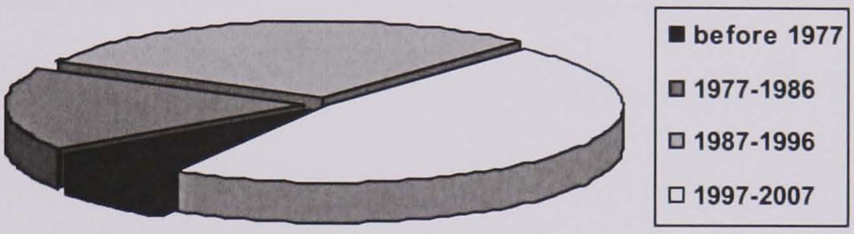

Figure 4.1: The pie chart compares quantitatively the cited papers in table 4.1 according to their publication dates.

It is not the intention here to present any of these in detail, but rather to summarise the main ideas as platforms for the research at the empirical stage. In the previous chapter, the meaning and the principles of complexity, chaos, and fractal theories and the relationship between them were presented. It was also argued that cities can be better understood through these new theories as their forms and functions exhibit the main features of complex systems. In this chapter, the literature will be reviewed to see how these theories may be applied to architecture, planning, and design. The chapter, therefore, comprises two main parts highlighting some of these applications under the terms fractal architecture and fractal cities.

4.1 Part One: Fractal Architecture; Applications of Complexity Theory and Fractals in Architecture

4.1.1 Applications of fractal concept in architectural design

Although there is no generally acceptable definition for the term fractal architecture, broadly speaking, two different mainstreams can be identified in the recent literature. Fractal-designed architecture and fractal assessments of architectural products are the focal interests of two groups of architects, designers, and researchers who have investigated the possible application of fractal geometry in architecture. They have approached the concept from two different viewpoints:

1. *The fractal concept as a critical tool*: The approach seeks to measure the complexity in the form of a design project. It is based on calculation of the fractal dimension of architectural design outputs to enable their assessment and evaluation.
2. *The fractal concept as a design tool*: This approach attempts to simulate natural forms or apply similar shapes of different sizes at the different scales of a design project. It seeks to create a complex form underlying subtle order at different layers of an architectural structure, claiming a resemblance to what happens in the creation of natural forms.

In both approaches, fractal geometry provides a quantifiable tool to describe the complexity in the physical appearance of an architectural product and the extent to which it qualifies as 'fractal'. The following two sections discuss each approach in more detail.

4.1.1.1 <u>The fractal concept as a critical tool</u>:

Fractal dimension measurement suggests a quantifiable tool to judge mathematically the extent of complexity (fractal quality) manifest by a design. A number of researchers have measured fractal dimension to evaluate critically architectural and urban elements, such as work by Bovill (1996) for comparisons of building facades, Cooper *et al* (2008) for evaluation of street vistas, and Stamps (2002) for analysis of urban skylines. Bovill (1996, p.119) suggests that the fractal dimension of a design can be measured and used as a critical tool. He claims that 'the lack of textural progression could help explain why some modern architecture was never accepted by the general public' (Bovill, 1996, pp.5-6).

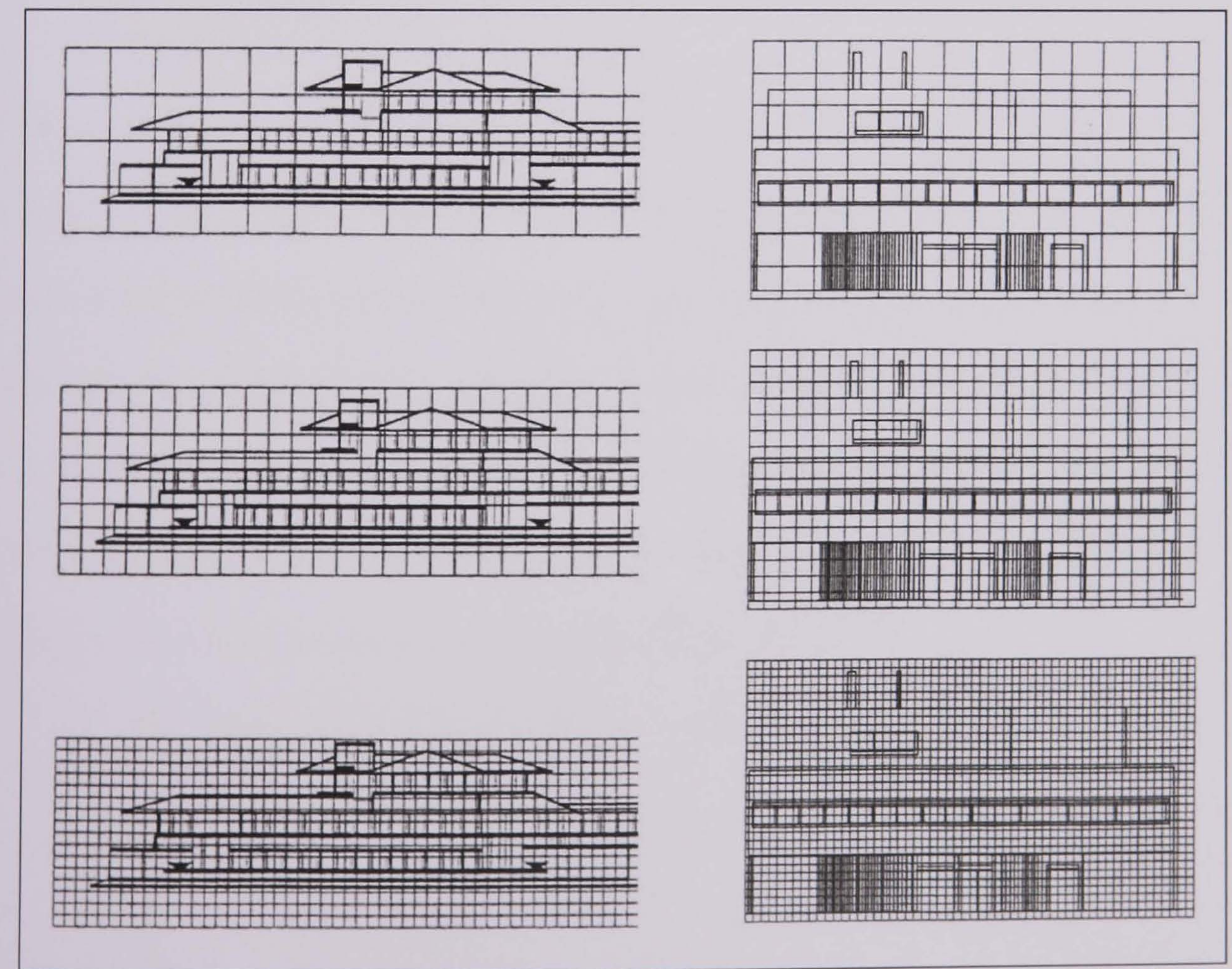

Figure 4.2: Left, box counting grids placed over the elevation of Frank Lloyd Wright's Robie house. Right, the front elevation of Le Corbusier's Villa Savoye with a box counting grid over it. (Bovill, 1996, pp.120, 140)

Box counting, as explained in the previous chapter, is a convenient method to measure fractal dimensions of complex forms such as architectural elevations and urban facades. For instance, Bovill (1996) has employed this method to compare two facades, one from Frank Lloyd Wright's Robie house (figure 4.2, left) and the other from Le Corbusier's Villa Savoye (figure 4.2, right). In both cases, he counted the number of boxes occupied by details that can be perceived at a range of box sizes. The results are summarised in Table 4.2.

The Elevation of Robie house		
Box count	**grid size**	**grid dimension**
50	1/16	12 feet
140	1/32	6 feet
80	1/64	3 feet

The Elevation of Villa Savoye		
box count	**grid size**	**grid dimension**
100	1/14	8 feet
268	1/28	4 feet
675	1/56	2 feet

Table 4.2: left, the result of box counting for the elevation of the Robie house. Right, the result of box counting for the elevation of the Villa Savoye. (Derived from Bovill, pp.119, 141)

Bovill calculated the fractal dimensions of the facades by simply using these data in equation 3.4 (see Chapter Three, section 3.3.2). The calculation reveals that the Robie house has fractal dimensions of 1.485 and 1.441, while Villa Savoye has fractal dimensions of 1.422 and 1.333. These figures show that within the range of scales from 12 to 2 feet, the Robie house has a slightly more complex form. However, the differences will be more obvious when we examine the two cases from a closer view, from 2 feet to 1.5 inches. This result is summarized in following table:

Box counting at the window scale of Robie house		
Box count	**grid size**	**grid dimension**
31	6	6 inches
102	12	3 inches
315	24	1.5 inches

Box counting at the window scale of Villa Savoye		
box count	**grid size**	**grid dimension**
29	12	2 feet
68	24	1 feet
136	48	6 inches

Table 4.3: The result of box counting for the Robie house (Left) and for the Villa Savoye (Right) at the range of scales from 1/6 to 1/48. (Derived from Bovill, pp.119, 141)

Again, fractal dimensions can be calculated based on the tabulated information. Interestingly the sequential dimensions are 1.721 and 1.626 for the Robie house while they are 1.233 and 1.00 for the Villa Savoye. Bovill (1996, p.143) has made the following important comment:

> 'At these smaller scales, where the box counting dimension for the Robie house remained high, the dimension of Villa Savoye dropped off to 1.00, indicating a lack of progression of detail. Wright's organic architecture called for materials to be used in a way that captured nature's complexity and order. Le Corbusier's purism called for materials to be used in a more industrial way, always looking for efficiency and purity of use.'

Fractal analysis of the Robie house shows that Wright designed the building with a cascade of detail from the organization of the building's overall form to the stained glass designs for the windows. Bovill (1996, p.127) states that 'when Wright was practicing architecture and writing about it, the concept of fractal geometry and its relationship with natural forms did not exist'. However some of his writing approaches the concept very closely:

> 'Quite a different form may serve for another, but from one basic idea all the elements of design are in each case derived and held well together in scale and character. The form chosen may flare outward, opening flower like to the sky; another, be noncommittal or abruptly emphatic, or its grammar may be deduced from some plant form that appealed to me.... But in every case the motive adhered to throughout so that it is not too much to say that each building aesthetically is cut from one piece of goods and consistently hangs together with an integrity impossible otherwise' (Wright, 1955, quoted in Bovill, 1996, p.127).

Providing a fractal interpretation of Wright's statement, Bovill (1996, p.128) writes that 'the last sentence in the quote brings to mind images of the fractals like Julia sets [see figure 3.21, Chapter Three]'. Julia sets display a wealth of detail at any level of magnification. This wealth of detail is the result of a very simple central concept, iteration'. The first sentence in the quote calls for all the elements of the design to be held together in "scale and character" by one basic idea. Bovill commented that '... this brings to mind the simple rule systems that are used to generate fractal forms like the Koch island that are at once very complex and very simple, since any small part is similar to the whole'.

In the middle of the paragraph, Wright (1955) refers to the natural source of form generating his ideas. He clearly used nature for inspiration, however, as Bovill (1996) states, his buildings do not look like trees or bushes. Instead, he was looking beyond the outward appearance of natural forms to the underlying structure of their organization. According to Bovill (1996, p.128), 'this is a fractal concept… One of the central features that fractal geometry tells us about nature is that the nature is not flat. Nature displays an almost infinite number of scales of length. There is a never ending cascade of interesting form that comes in clusters and only rarely displays perfect symmetry'.

In short, what Bovill suggested is that natural forms do have an underlying organizational structure, and fractal geometry provides a clear method of understanding and describing that structure. This method can also be used as a design tool for creating fractal structure in architecture. As Jencks (1997, p.43) stated, '…those who style themselves organic architects often mimic nature's patterns of organization and, in designs, naturally repeat a formal idea at many scales and, just as inevitably as a flower, provide several foci'. The ideas and examples of this type of approach are discussed in the next section.

4.1.1.2 The fractal concept as a design tool:

> 'Could Fractals produce rich architectural ornament that could be cheaply computer produced? Could fractals be used as paradigms for individual buildings or conurbation design? Could they be a formula for automatically achieving that extreme degree of variety recognized as essential to human well being – but impossible to specify manually?' (Smith, 1990; quoted in Cooper, 2000, p.177)

In addition one could also ask: should fractal geometry be employed as an essential substitute for Euclidean geometry in architecture and urban design? To answer these questions, the following sections will examine two groups of buildings to which the fractal concept could have arguably been applied. The first can be categorised under the term fractal style referring to the concept through the idea of "self-similarity", while the second expresses the idea of "fractal rhythm" as a visual quality or richness in design. Both categories have arguably the potential to provide a tool for designers to create something in coherence with the environment.

I) Group one, the idea of self-similarity:

> 'It is a truism that all organisms and architecture must show some self-similarity…' (Jencks, 1997, p.43).

> 'Fractal design and its use in architecture is potentially one of the most obvious, practical and applicable uses of the new sciences' (Cooper, 2000, p.178).

Although the role of self-similarity in producing fractals is relatively a very new concept, throughout history there are many examples in which the idea has been applied. Before 1970, architects had no idea about fractals and just used the self-similarity technique to build up a hierarchical structure imitating forms in nature. Joye (2007, p.311) writes that 'The deployment of fractal principles in art and architecture seems to be a phenomenon of all times, and is in no way restricted to the period after the systematic mathematical understanding and description of fractals from the 1970s onwards'.

Figure 4.3 illustrates the idea of self-similarity in two Hindu temples. Their surfaces are similarly rough, no matter which scale is used, and some of the architectural elements have gone through a transformation by which their size and position have been changed. For example, the completely parabolic form of the temple can be found in a modified way in smaller parts on the surface. These are, in fact, the characteristics that we see in fractal objects.

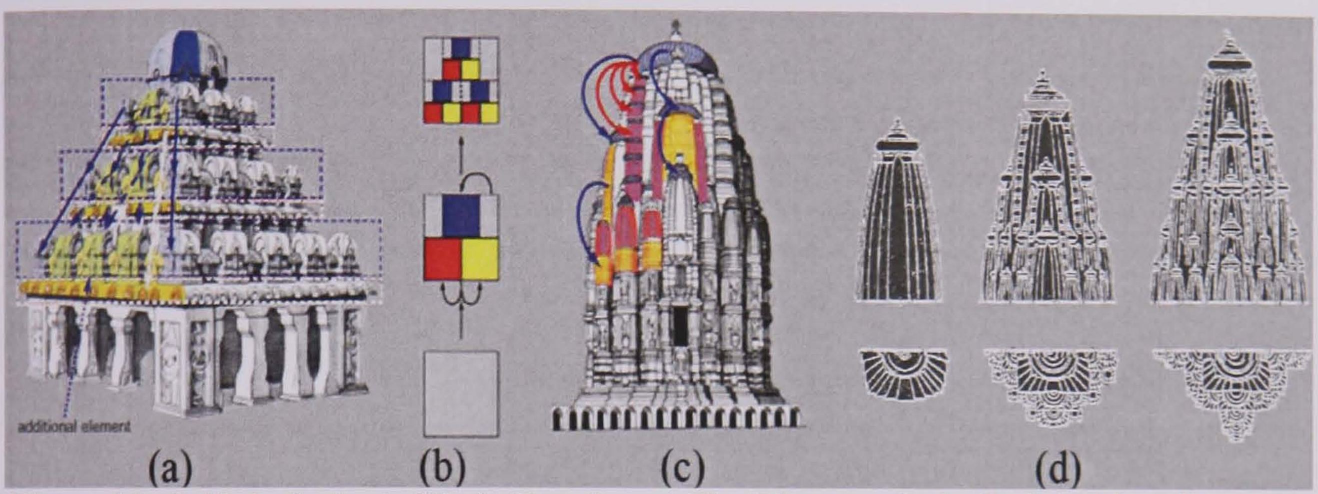

Figure 4.3: Self-similarity in Hindu Temples. a) The Dharmaradscha Rath in Mamallapuram, India. b) The fractal attractor drawn by Lorenz shows how the overall shape generated. c) Temple of Rajarani, in Bhuvanesvar, India. d) Fractal interpretation of the temple, the simulation created by Trivedi. (a, b, c from Lorenz, 2003, unpaginated; and d from Trivedi, 1989, p.252)

Fletcher (1975), Crompton (2002) and Lorenz (2003) examined the detailing features of Greek and Gothic styles, comparing them with some mathematically produced fractals, and revealed amazing geometrical analogies. The prominent examples of self-similarity patterns can be observed in Gothic architecture. In the Cathedral of Cologne, for instance, the pointed arch is transformed in size and position and can be found in the entrance, above windows and all over the external and internal surfaces (figures 4.4c, 4.4d).

Figure 4.4: Self-similar patterns in Gothic elements (pointed arch, gable, etc). Left (a, b), the Cathedral of Lincoln, England. Right (c, d), the Cathedral of Cologne, Germany. (Lorenz, 2003, unpaginated)

The Lincoln Cathedral, in England, is another example in which the fractal concept of self-similarity can be observed. In the tracery of the Angel Choir (figure 4.4, a, b), the lower level contains eight small but high vertical cuts, formed by the mullions, in each case two together with a quatrefoil crowned by a pointed-arch. As Lorenz (2003, unpaginated) describes, 'In each case such a pointed-arch also holds together two of the remaining four combinations'. This means that the fractal concept exists at all levels of scale. The order underlying the bifurcation of vertical elements – whether perceived as "Y-shape" or "pointed arch-shape" (figure 4.5a) – is dominant at all scales on both interior and exterior surfaces. It forms the columns, arches, gables, spires, ribbed-vaults, etc (figures 4.4 c, d, 4.5 a, b).

The interesting fact in Gothic style is that each element consists of rich detailing layers. Small details obey the same principle as the large elements. The window of Saint Mary's chapel of the Cathedral of Wells (figure 4.5c), for instance, has a three-pointed curved structure repeated at different scales – similar to the Sierpinski Gasket, but in this case the middle part is not taken away (Lorenz, 2003). The rose window of the Cathedral of Chartres is another example of a self-similar pattern (figure 4.5d). The main circle around the whole rose window is reduced and repeated in the middle part and surrounded by twelve small circles. Schneider (2003) explained in detail how each circle has been embedded one in another following a geometrical order. He claims that the whole structure of cathedral is proportional to the rose window; he also writes that 'the geometry of this window is an integral part of the design of the entire structure, which was composed as an interconnected whole. ... I suspect that the whole front is an expanded version of the window'.

a

b

c

d

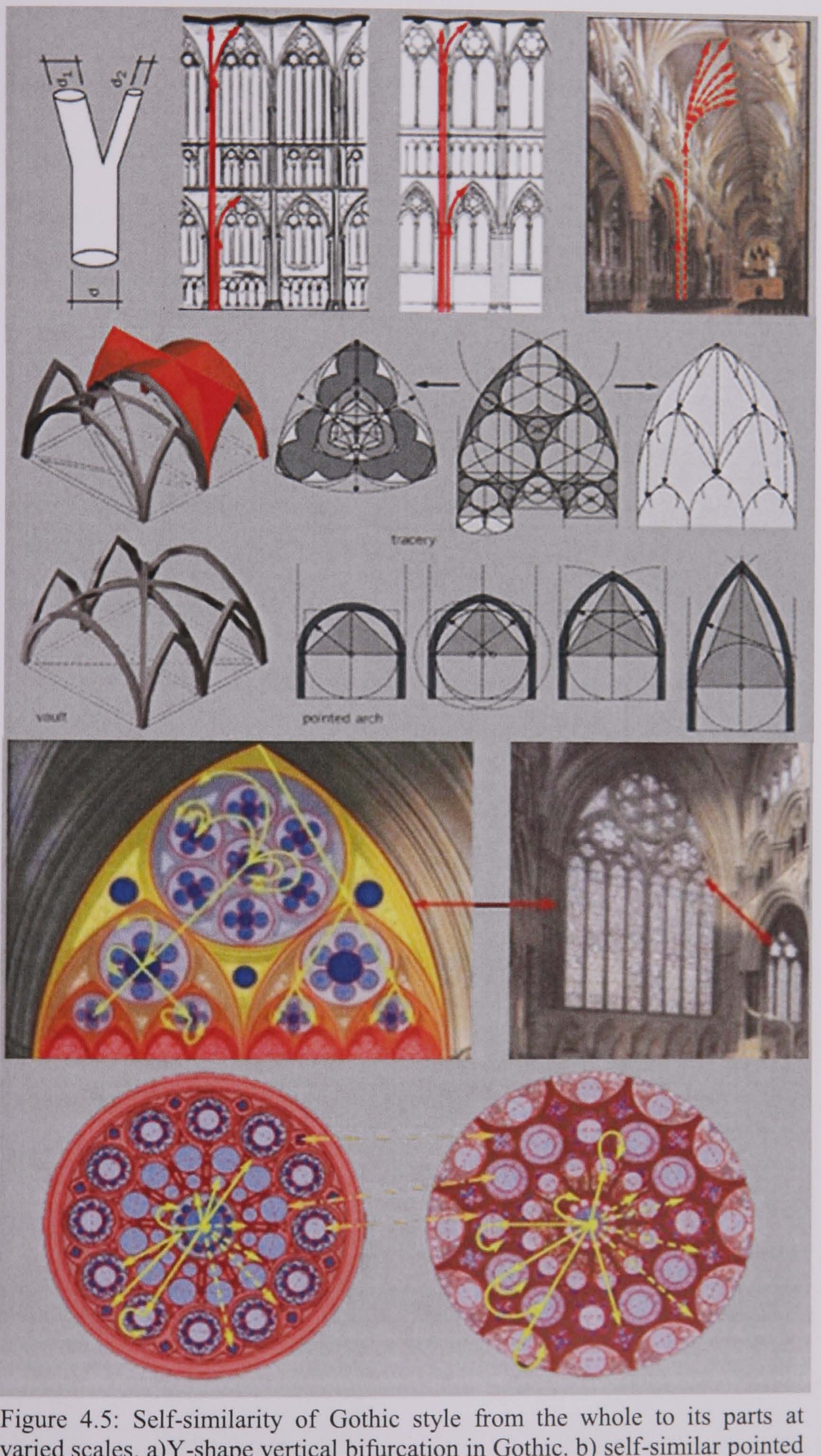

Figure 4.5: Self-similarity of Gothic style from the whole to its parts at varied scales. a)Y-shape vertical bifurcation in Gothic. b) self-similar pointed Arch structure. c) The tracery of the "Angel Choir" of the Cathedral in Lincoln, Great Britain. D) Rose windows of the Cathedral of Chartres. (Lorenz, 2003, unpaginated)

Crompton (2002) has found an interesting analogy between the well-known fractal, the Koch island, and the plan of a Gothic column (Figure 4.6). In both the column and the fractal, the solid portion resembles the negative space. Crompton (2002, p.455) states that 'Gothic mouldings are scaling forms although there must be principles of proportion and ordering at work that go beyond the scope of the algorithm, they seem to be fractal'.

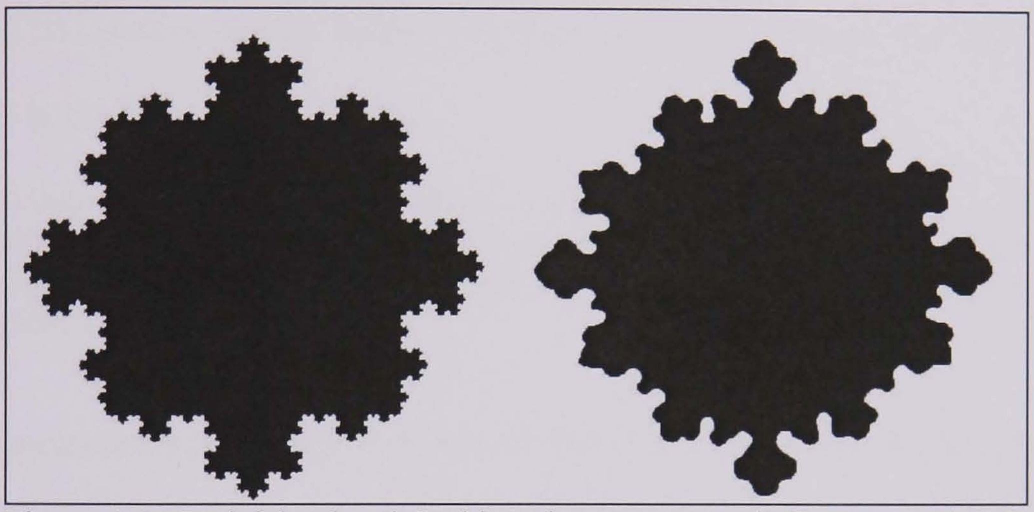

Figure 4.6: Koch island and Gothic column compared. (Crompton, 2002, p.455)

In Figure 4.7, Crompton (2002, p.452-454) provides another analogy between a Doric cornice and the well-known fractal 'the devil's staircase' produced first by Mandelbrot (see Mandelbrot, 1983, p.80). In the case of the Doric cornice (figure 4.7, left), its shape roughly repeats itself inwardly over four stages. Figure 4.7 (right) shows similar stages of self-similar steps in the Devil's staircase where the parts in the boxes are stretched to the proportions of the original.

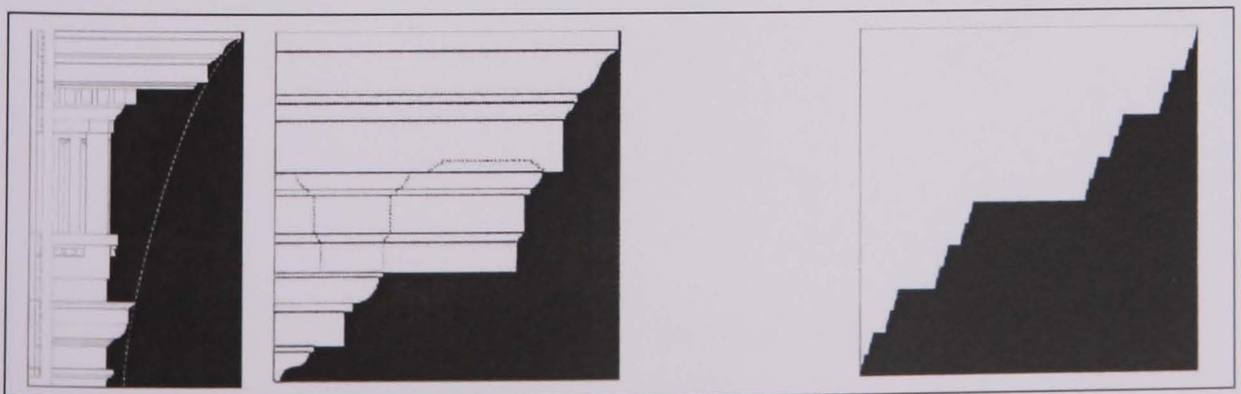

Figure 4.7: A denticular Doric entablature (left) and the Devil's staircase (right) compared. (Crompton, 2002, pp.452-453)

The famous British architectural critic, John Ruskin, gave some advice, which Crompton (2002) interpreted to what we now call fractal design. Ruskin (1903) appreciated natural forms and encouraged architects to apply the laws of nature in their work - what he called 'laws of composition'. In fact, the first written description of self-similarity was by him (Crompton, 2002; Unrau, 1978). Ruskin (1903) believed that the "continuity" in nature is the result of "successive similar shapes" accompanied by some gradual change. He explained it in the following statement:

> '... an orderly succession to a number of objects more or less similar ... most interesting when it is connected with some gradual change in the aspect or character of the objects' (Ruskin, 1903, vol.15, pp. 170-171, also quoted in Crompton, 2002, p.457).

The image produced from Ruskin's advice in1858 (figure 4.8) well illustrated what he meant about 'hierarchy and similarity', and surprisingly, it is very similar to what Mandelbrot drew by computer in 1967, and called a 'fractal tree'.

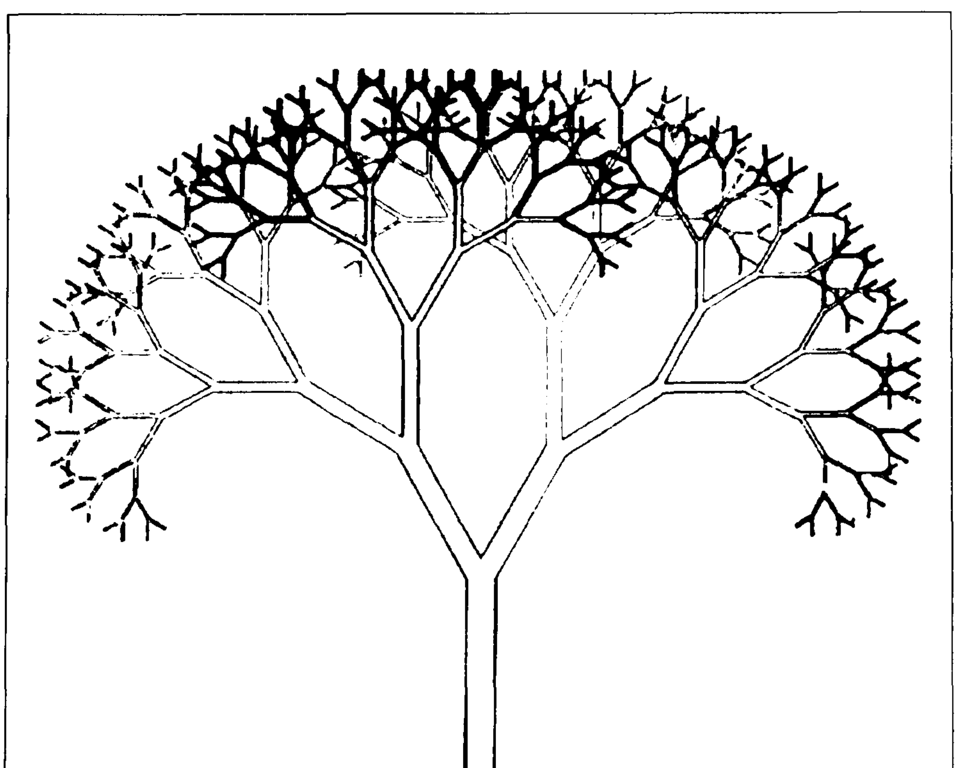

Figure 4.8: Ruskin's fractal tree – Sketch by a clerk of the works drawn in 1858. (Crompton, 2002, p.458)

Crompton (2002, p.451) argues that 'a building is fractal if it repeats and multiplies a form, such as a pointed arch, over several orders of size. Gothic buildings aside, not many buildings actually do this'. While he believes that the memorial at Thiepval by Lutyens in 1925 (figure 4.9, left) is an example of fractal design, it might be argued that this is not exactly similar to what we see in nature. Crompton (2002) admits that modern examples with fractal quality are even harder to find. He suggests that 'the well known flats in west Amsterdam by architects MVRDV (figure 4.9, right) repeats a box shape over three stages'. While this example clearly shows the attempt of its architects to produce a piece of fractal architecture, the opportunity to carry the progression below the size of the balcony is not taken and therefore it misses the small-scale detailing that we see in nature.

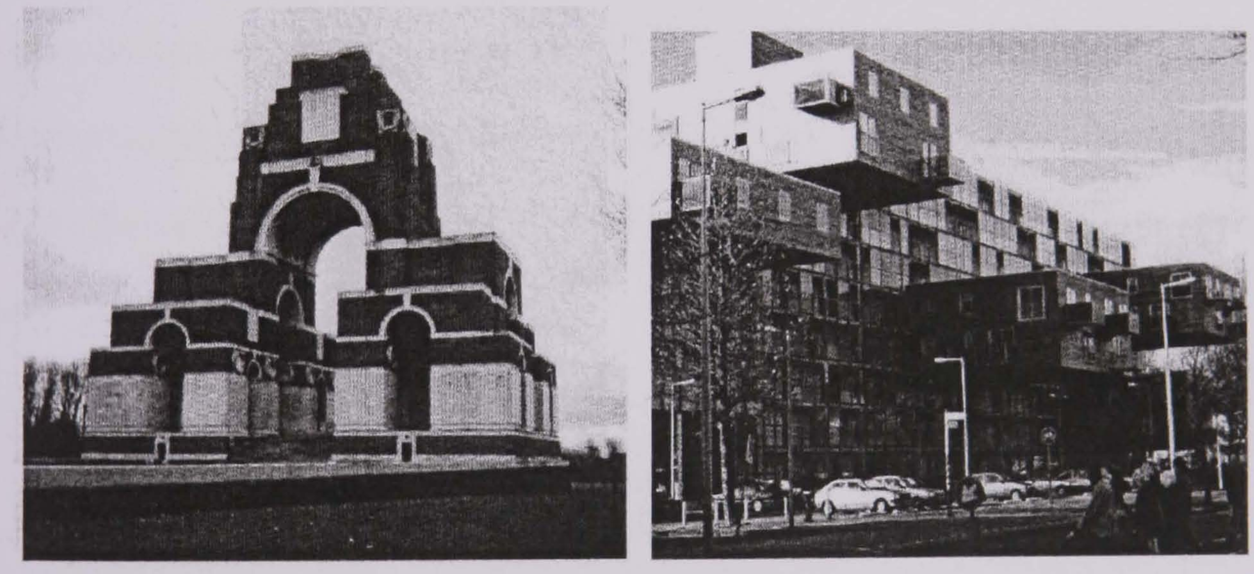

Figure 4.9: Left, Thiepval memorial by Lutyens in 1925 demonstrates three stages of self-sameness. Right, The Amsterdam housing by MVRDV in 1995 (1995) demonstrates three stages self-similarity. (Crompton, 2002, p.451)

It should be also recalled that a fractal shape contains the property of 'self-similarity' – not self-sameness. Jenks (1997, p.43) clearly makes this distinction: 'Self-similarity is a transformational similitude – not an exact replication.' In this sense, the forms in the Thiepval memorial can be considered more as self-sameness while The Amsterdam housing demonstrates self-similarity. Nevertheless, it can be argued that neither achieved a sufficiently high level of physical complexity to be called fractal architecture.

The Price house designed by Bruce Goff can be claimed to be exemplary in terms of self-similarity (figure 4.10). Jencks (1997, p.44) described this house in the following way:

> 'Self-similar triangles, hexagons, and trihexes organize his Price house – from very large to very smallest detail. Sixty degree angles, their multiplication and subdivision, recur in all sorts of forms and materials.... its conversation "pit" is hexagonal, the wall of the music room is triangular to deflect sound, and various self-similar wedge shapes emerge from the ceiling in the form of acoustic decoration'.

Jencks' description emphasises two key factors by which a piece of architecture can be considered as fractal: 'self-similarity' and 'details'. As can be seen in the Price house show these two properties over a wide range of scales, from small to large. Following some simple geometrical rules, every element has been connected to the element next to it and to the whole. However, there is no sign of an exact replication or symmetry. Each element, each part, and each corner has its own character. It has a holistic order, but it also has a higher degree of complexity, since the pattern is everywhere slightly different. In short, the various shapes are harmonic, related and self-similar, but hardly ever self-same.

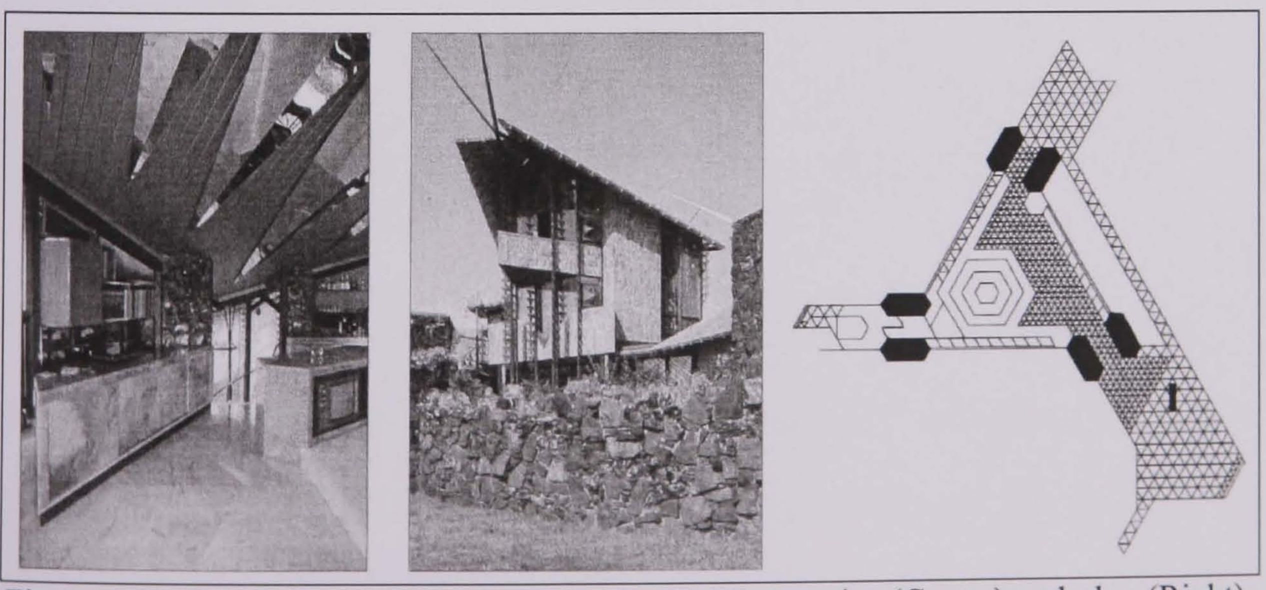

Figure 4.10: Bruce Goff, Price house, interior (Left), exterior (Center) and plan (Right). Fractal shapes extend through the glass cullet, details and structure. (Jencks, 1997, pp.42, 44)

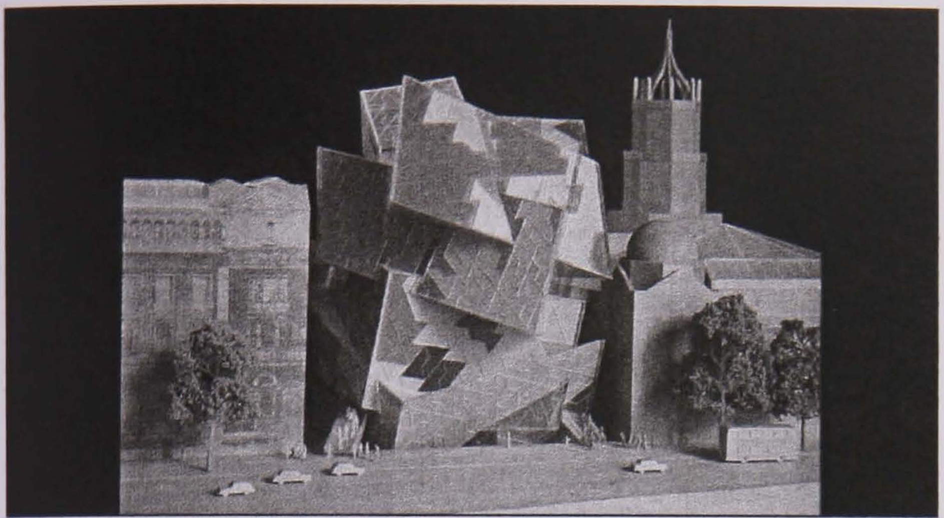


Figure 4.11: Daniel Libeskind, proposed addition to the Victoria, Albert Museum (V & A), London, 1996. Six tilted trapezoids spiral through each other and form a new, structurally sound shape. Tiles in V- and L-forms are in different scales and colours – self-similar fractals. (Jencks, 1997, p.13)

Some contemporary architects and designers deliberately have tried to apply self-similarity to their designs. In a project for an addition to the Victoria, Albert Museum in London (figure 4.11), Daniel Libeskind has attempted to produce a fractal architecture that jumps out of the ground in a series of six leaps. Six boxes push through each other, part cubes, part rhomboids. The flat walls, as calculated by the engineer Cecil Balmond, actually become the structure, allowing column-free interiors, so the crushing shapes have a functional rationale. Jencks (1997, p.13) described Libeskind's work as:

> 'A set of six fractal shapes at the large scale are supplemented by smaller "fractiles" at three lesser scales. These self-similar tiles are shaped like an angled L- or V-boot, something not far from the larger rhomboids, so there is a unifying pattern. The L-forms dance over the surface in minor-image, flips and rotations – standard steps, as shown by the million tiles within the V & A.'.

Whether we accept Jencks' claim and call this project 'fractal architecture' or not, it demonstrates how a well-known architect tried to employ self-similarity to produce something more complex and sophisticated. An example where we can apparently find an expression of the fractal concept is the interior refurbishment of Storey Hall in Melbourne (figure 4.12). On the walls, stage, and the auditorium ceiling (figure 4.12d), the fractal grammar based on complexity theory is played at different scales. The architect has used computer assistance to derive a new grammar; however, he could not extend the same discipline to the whole volume of the existing building structure (figure 4.12c).

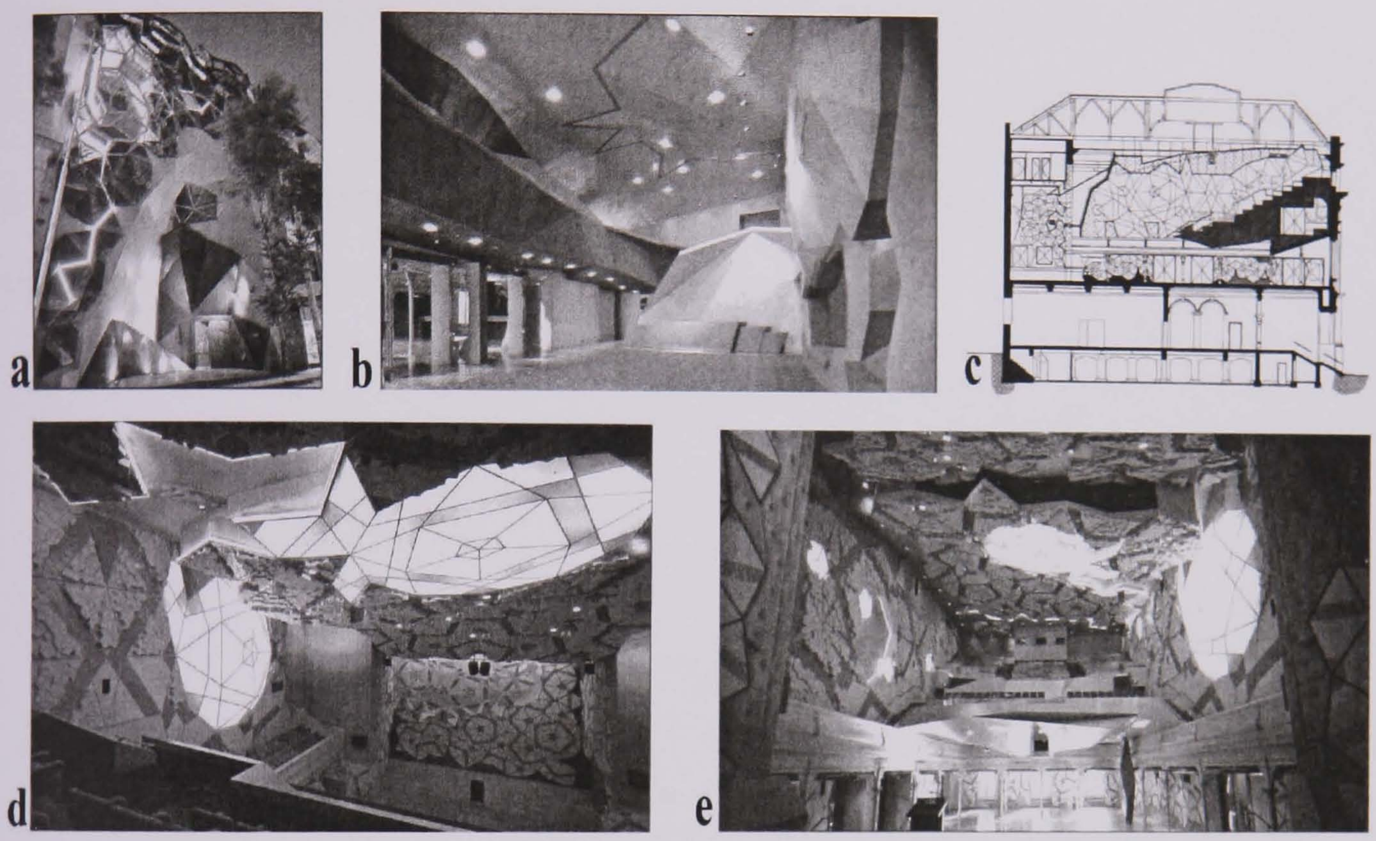

Figure 4.12: Storey Hall, by ARM group (Ashton Raggatt McDougall) in Melbourne, 1993-96; fractal forms are based on the aperiodic tiling pattern devised by Roger Penrose – a new always-changing order for urbanism. (Jencks, 1997, pp.179-181)

Having analysed some of the works of contemporary designers who have referred to self-similar fractal as a design style (the first group), the second group provide another perspective towards fractal architecture which is more related to the idea of organic architecture.

II) Group two, the idea of fractal rhythm (unity with variety):

> 'an understanding of fractal rhythms can open up an endless supply of design ideas for the architect or designer, interested in expressing a more complex understanding of nature' (Bovill, 1996, p.6).

The second group of buildings that have fractal quality are those having a number of elements obeying a kind of rhythmic order at different levels of scale. In other words, they exhibit "unity with variety" rather than "self-similarity". This method treats a building like a landscape where elements of a particular scene are related without being necessarily self-similar. For instance, Such potential can be seen in the work by Lucien Kroll (figure 4.13) where a deep cascade of shape and detail is displayed in the diverse residential designs. In this sense, most old buildings could also be claimed to have fractal quality because they exhibit variety according to a number of elements, layers and shapes used to construct an overall unity.

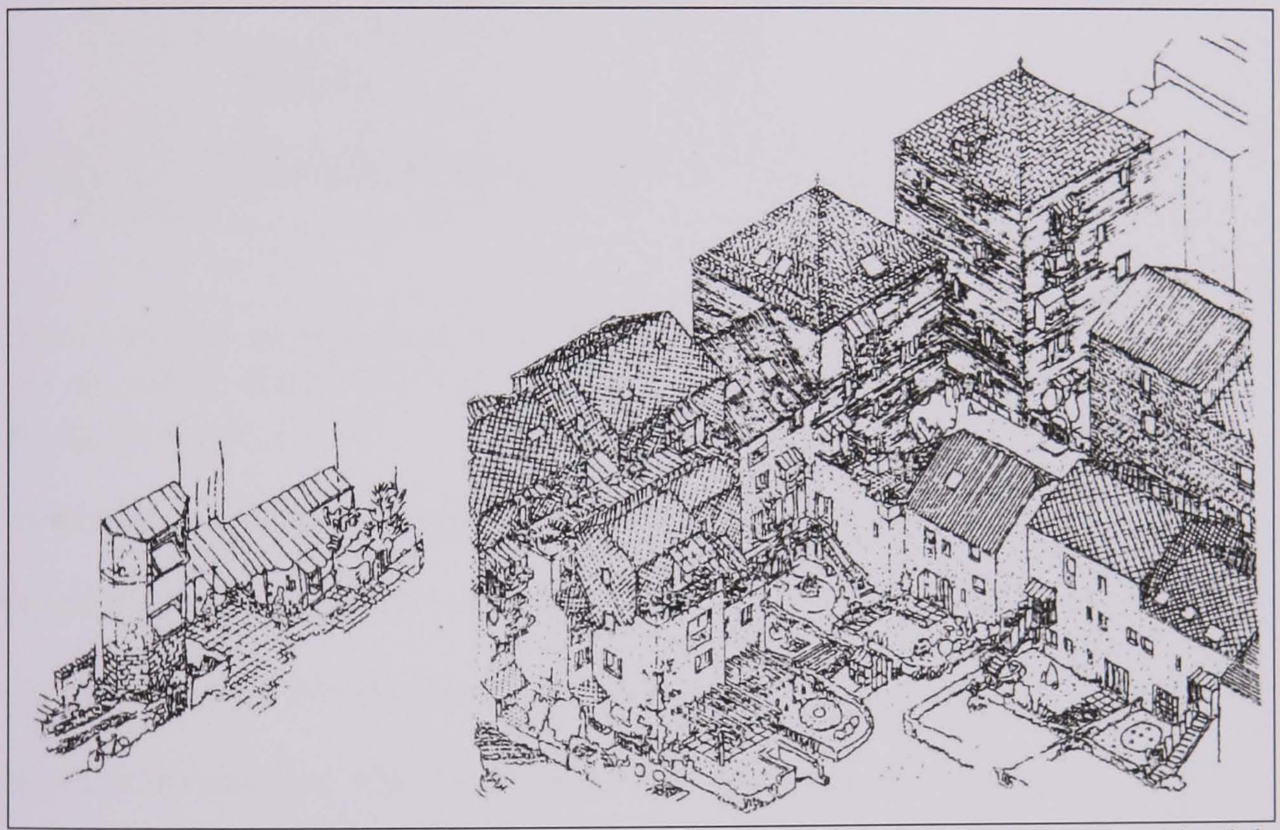

Figure 4.13: A deep cascade of shape and texture is displayed in the diverse residential designs of Lucien Kroll. (Bovill, 1996, p.8)

This is an easier way for a building to be fractal than if all its parts are made to have something in common. However, 'most modern buildings are not fractal even in this easier sense because they use large blank surfaces, avoid decoration, and use simple forms, such as single block, rather than one broken into subsidiary volumes' (Crompton, 2002, p.452). Even the examples given in figure 4.9 would hardly considered as fractal architecture. Although they illustrate three stages of self-similarity, they do not expose a range of small-sized detailing lower than 2 metres. Crompton (2002, p.452) concluded that 'these reasons why modern architecture is not fractal are the same reasons that are often given to explain why it can appear oppressive and unnatural' (refer back to the discussion in part two of chapter two).

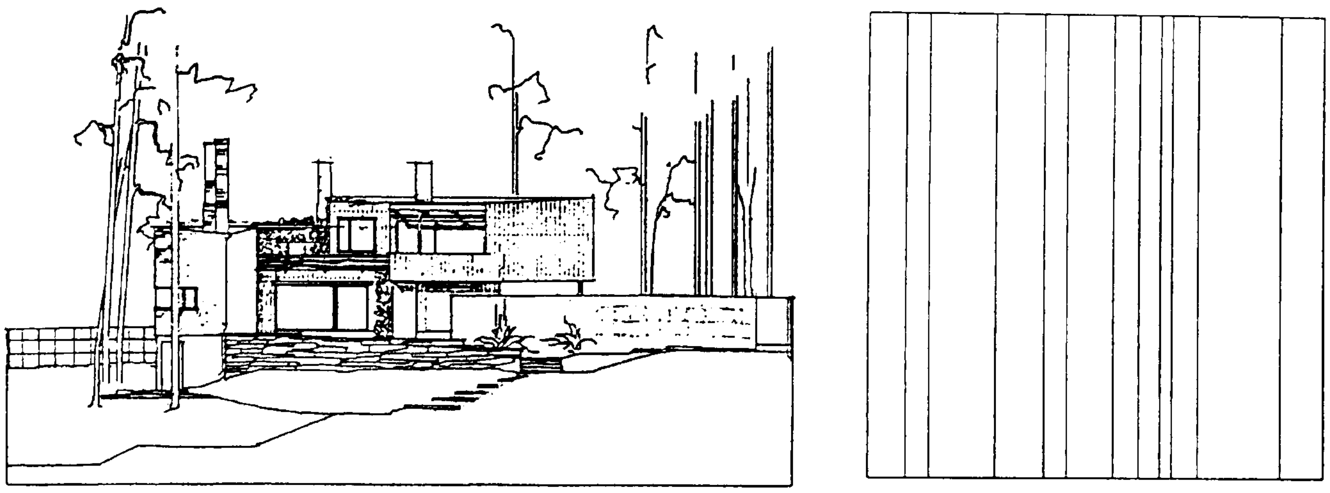

Figure 4.14: Left; an elevation of Aalto's home and office. Right; a fractal planning grid with only the vertical rhythm lines laid out. The rhythms in this figure are based on D_f =1.7. (Bovill, 1996, pp.112-113)

Nonetheless, there are some modernists that could be considered as naturalists (e.g. Aalto, Wright) who produced some rhythms similar, and in response, to what exist in the environment and the site of projects. It can be claimed that they achieved a type of fractal complexity in coherence with the environment without even being familiar with the term fractal or even without restricting their work to the concept of self-similarity. While they designed well before the science of fractals was articulated, nevertheless it can be claimed that they virtually invented fractal architecture (Jenks, 1997). For instance, much of Alvar Aalto's work displays the complex rhythms of nature. Figure 4.14 (left) illustrates an elevation of Alto's home and office and Figure 4.14 (right) is a fractal rhythm with the dimension of D_f = 1.7; as Bovill (1996) noted, it is similar to the tree spacing in the background of Aalto's home and office. He writes:

> 'Note how the variation in window and wall panel size echoes the variability of tree spacing in the forest' (Bovill, 1996, p.112).

As nature has fractal geometry (shown by Mandelbrot), an architect intending to design a project in coherence with its natural environment can imitate the fractal rhythm existing in that environment and distribute the lines and elements of his design with the same rhythm to capture its complexity. Inspired by Alto's work, Bovill (1996, p.6) also suggested that 'the fractal dimension of a mountain ridge behind an architectural project could be measured and used to guide the fractal rhythms of the project design'. If both heights and widths of each house have been varied according to the fractal distribution of the natural forms in the background (figure 4.15), the project design and the site background would then have a similar rhythmic characteristic.

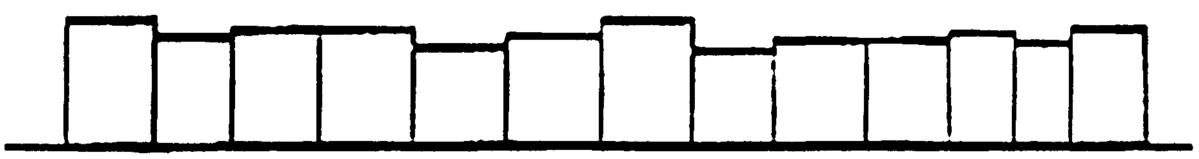

Figure 4.15: Fractal distribution of height and width for a row of townhouses. (Bovill, 1996, p.6)

This type of approach is similar to what can be seen in 'organic architecture'. Jencks (1997, p.43-45) suggests that virtually the work of all who are interested in organic architecture should show fractal characteristics such as 'self-similarity', 'unity with variety', 'strange attractor', etc. The Bavinger, Garvey, and Price houses designed by Bruce Goff – in 1950, 1952 and 1956 respectively – are exemplary in this respect. In the Bavinger house (figure 4.16), for instance, Goff uses a spiral shape to organize a flow of movement around and up a ramp which is interpreted by Jencks (1997, p.45) as 'strange attractor' similar to fractal patterns in complex systems. It exhibits the dynamic, local and non-local interconnections, simultaneously unfolding and enfolding in the gesture of attractors in a living system (compare it with Lorenz's strange attractor, figure 3.5).

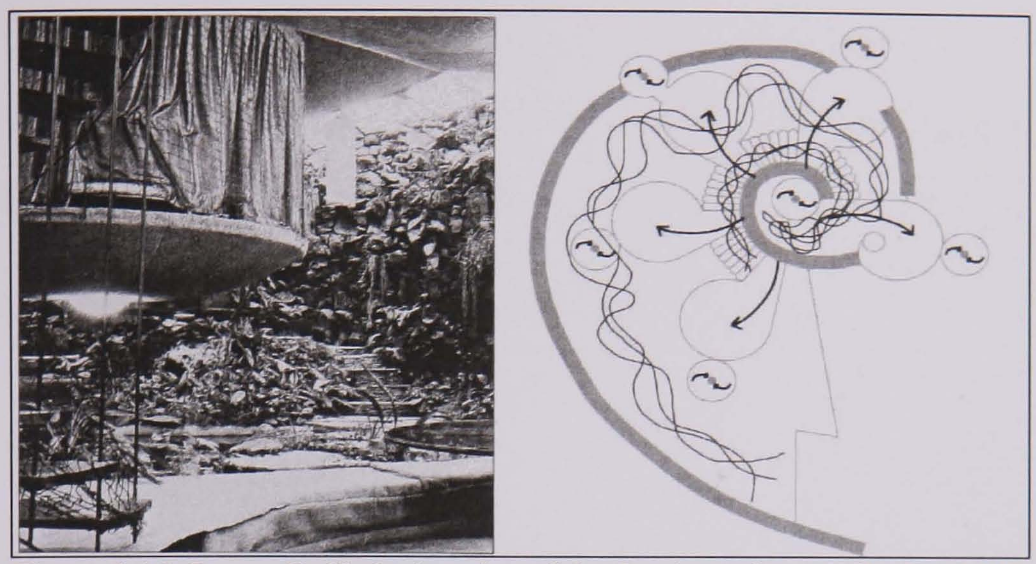

Figure 4.16: Bruce Goff, the interior of the Bavinger house. (Jenks, 1997, p.45)

Cooper (2000, p.178) also refers to the Bavinger house and states that '…visually it seems to have fractal characteristics, but how, other than by being interesting to look at, does it contribute to planetary survival? How does it feel to live in? Is the form energy efficient?' in other words; can fractal architecture contribute to sustainability in order to make better places to live in future?

> 'If a constructive answer is not forthcoming then "fractalian architecture" is in danger of being seen as just another abstract design style' (Cooper, 2000, p.178).

To explore these questions further, a deeper picture of fractal architecture and its characteristics are required; otherwise, as Cooper suggested above statement, the fractal concept is in danger of being seen as just another abstract design style.

4.1.3 Fractal architecture

Are there any architectural products – buildings or urban spaces – that can be called 'fractal architecture'? If so, are there any criteria by which an architectural product may be assigned as fractal? Based on the discussion and examples in section 4.1.2, the answer to the first question is explicitly 'yes'. However, a precise and common-sense answer to the second question is not available. There is no generally accepted definition to assure us as to what kind of properties or criteria can be assigned to distinguish typologically fractal architecture. This can cause ambiguity. We may think that a designed object has fractal quality whereas it has not. To overcome this problem, it might help to reverse the question and ask, "What is not fractal architecture?"

4.2.3.1 Non-fractal architecture:

Some of the seemingly complex buildings with self-similar patterns appear to be flat at closer observation, hence, should not be called fractal. For instance, The Jewish museum in Berlin and the Cinema Center in Dresden (figures 4.17, 4.18) might be mistakenly interpreted as if they have fractal property. Jencks (2002, p.247) believes that 'self-similar forms, angles, slashes and lines' in these two buildings exhibit a fractal grammar. However, in both cases, if they are observed at short distances (e.g. 3-4 metres), their forms and elements do not reveal any further self-similarity, details or textural progression. At that level, in fact, they seem to be flat; and the self-similarity did not progress more than two stages.

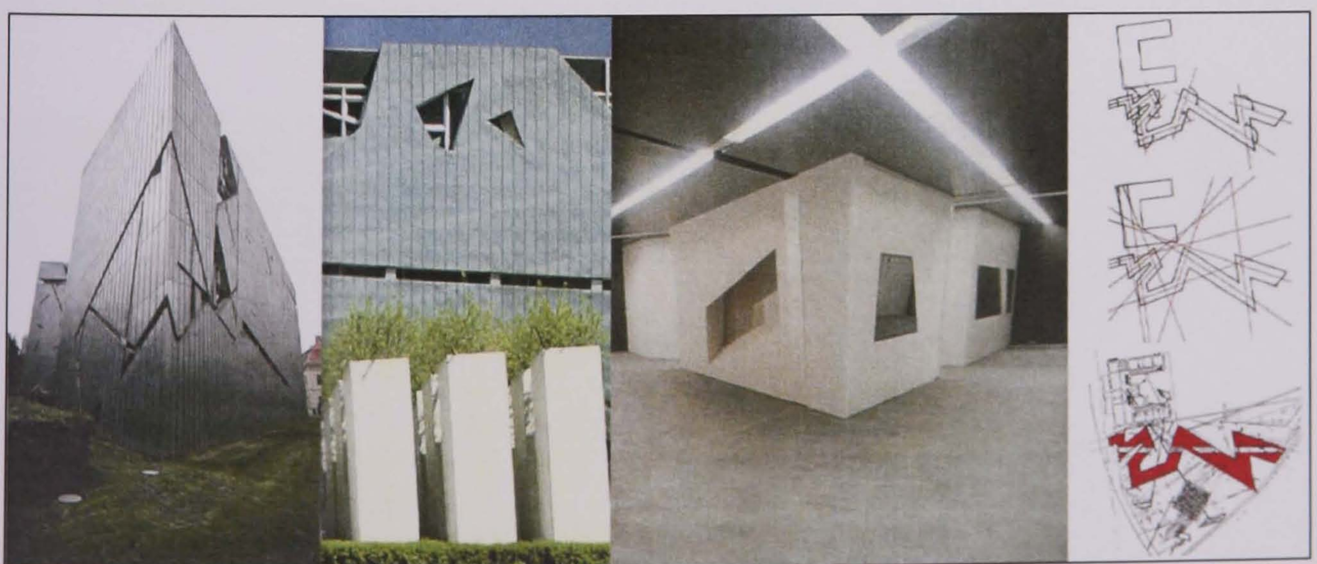

Figure 4.17: Jewish Museum, Berlin, Designed by Daniel Libeskind, 1989-2000. At the first impression may seem fractal while it is not. (Jencks, 2002, pp.246-248)

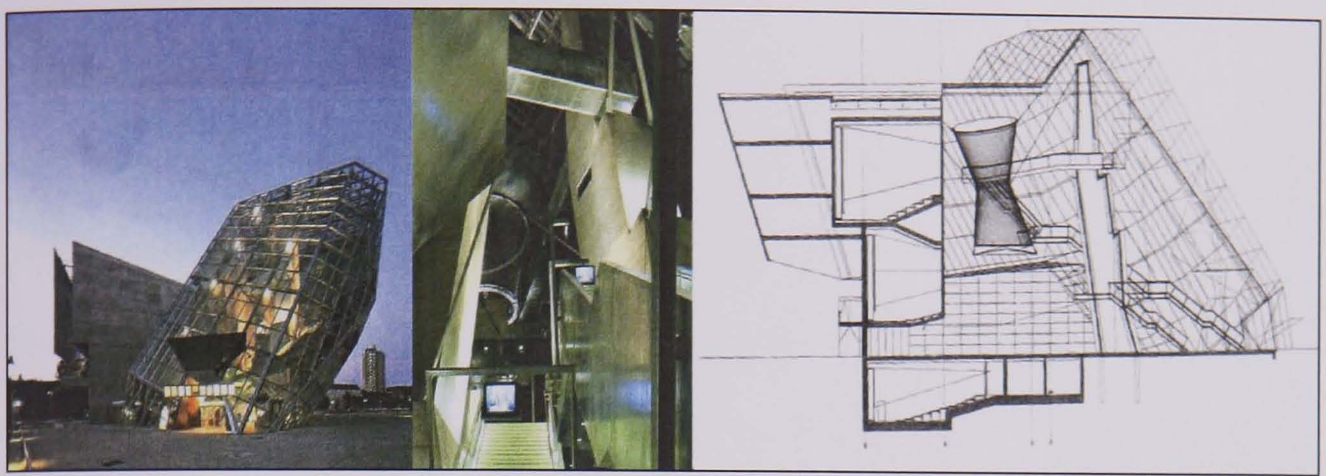

Figure 4.18: Cinema Center, Dresden, Designed by Coop Himmelblau, 1993-1998. Exterior, Interior and the section reveal some self-similarity but not create fractals. (Jencks, 2002, p.239)

The complex of Federation Square in Melbourne (figure 4.19) is another example where the architects – LAB with Bates Smart – attempted to employ fractal geometry as an organizing tool, but failed to apply it to the whole project successfully. The architects claim that 'the building dissolves the city grid to the north into the parkland to the south using fractal geometry at several scales to do so' (quoted in Jencks, 2002, p.262). What features of the form might create this impression in their minds and encourage them to make this claim? The seemingly dynamic texture does not make a logical relationship with the overall shape. It is just a repetition of a triangular Euclidian shape, and does not create the structural depth that we see in a fractal object in nature.

Figure 4.19: Federation Square, Melbourne, designed by LAB with Bates Smart, 1997-2002. The fractal concept in the mind of architect could not create fractal architecture. (Jencks, 2002, p.239)

In the same way, the examples given in the figure 4.20 cannot be called fractal architecture. Neither within their own structure, nor in the way their forms communicate with their environments, do they exhibit structures like fractals. In the following statement, Alexander (2002b) argues that the language used in these examples is not useful for creating a successful textural progression or what he calls a living structure.

> 'The Piano and Libeskind examples show idiosyncratic modernistic forms... which are not suitable as a source of schemata for living structure' (Alexander 2002b, pp.440).

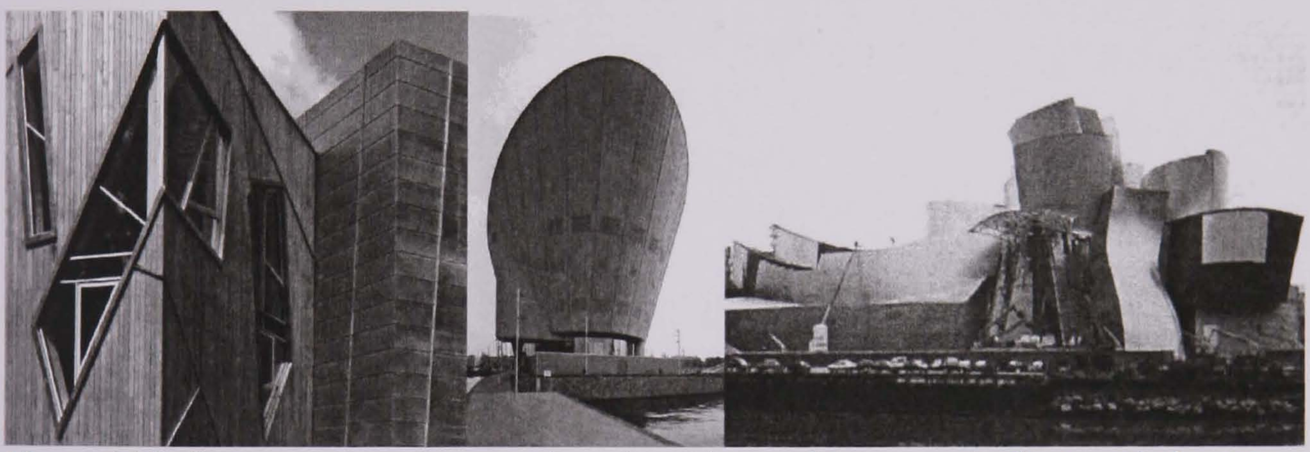

Figure 4.20: Some avant-garde examples of architectural language in the twentieth-century creating fabricated structure, not living structure. Daniel Libeskind's Felix Nussbaum Museum in Osnabruck (left), Renzo Piano's Center for Science and Technology in Amsterdam (middle), and Frank Gehry's New Guggenheim Museum in Bilbao (right). (Left and middle, Alexander, 2002, pp.439-440; Right, Jencks, 2002, p.239)

Alexander (2002) argues that even some of the attempts by modernist and postmodernist architects to create organic architecture are likely to fail. In the Community Center in New Caledonia (figure 4.21), for instance, the forms very roughly resemble (in outward shape only) their foreground natural context – a self-similar branching structure – however, 'its characteristics ... still does not correct the essential problem, the lack of unfolded geometry' (Alexander, 2002b, pp.400-401). According to Alexander (2002b), 'unfolded geometry' means that their forms are not generated in a step-by-step adaptation process which accepts changes over time.

Figure 4.21: Community Center, New Caledonia, Designed by Renzo Piano, Seemingly organic architecture, but can not considered as fractal architecture. (Alexander, 2002b, p.441)

A typical problem in modern architecture is that forms are not generated but 'fabricated' (Alexander, 2004). In short, a building or an urban space, which contains only one feature of complexity (e.g. self-similarity) but does not fulfil other aspects, cannot be considered as fractal architecture. In the following section, the research attempts to establish some features by which, a piece of architecture or an urban space can be evaluated as being fractal.

4.1.3.2 The key features of fractal architecture:

A number of theorists have suggested a list of properties to define the term 'good architecture' – e.g. Ruskin's (1903, pp.159-188) 8 rules for composition, Jencks' (1997, pp.167-170) eight criteria for architecture, and Alexander's (2002a, pp.143-242) 15 fundamental properties for living structures. However, none of the experts in fractal theory have yet provided an integral list of criteria by which the term "fractal architecture" can be explicitly defined. The list of criteria suggested in this section is not claimed to be comprehensive, but is intended to distinguish a fractal architecture from a non-fractal one.

Criterion 1 – Integrity and Multiplicity: A small number of elements cannot make complexity (see Chapter Three, section 3.2.2.1 for details). A fractal form exhibits complexity and its complex form is composed of a large number of elements from large to small scales. 'Its elements are impossible to count' (Crompton, 2002, p.459). Its complexity is revealed gradually – more and more detail and elements appear – as one gets closer. However, this multiplicity is not anarchic but follows an integral structure obeying some certain rules, which create similar patterns – fractal patterns. This echoes Ruskin's (1904) advice about good composition with scaling rules (see figure 4.8 in section 4.1.1.2). He suggested that an ornament or a building should be designed in a way that it is meaningful when seen at long, intermediate, and close range (see also Chapter Two, section. 2.1.3.2). This is only possible by applying details at different scales so that considerable numbers of elements work together in an integral whole.

Criterion 2 – Self-similarity/Self-affinity: This is the most familiar feature of fractal complexity, which the previous chapter discussed using a range of examples. Fractally designed objects contain self-similar patterns repeating at different sizes and scales. In other words, their small, medium, and large elements are proportional to the whole, following some mathematical or geometrical rules which create a logical hierarchy in form and structure. As Ruskin (1903) suggested, it is exactly what a good composition calls for – 'an orderly succession to a number of objects more or less similar' (Ruskin, 1903, vol.15, p.170). This also responds to Alexander's idea of 'levels of scale'.

However, self-similarity might be mistakenly described as rhythm, proportion, or simple repetition. Many successful architects apply some proportional order in their designs – for example 'the modulor' concept of Le Corbusier obeys rules of proportion (see the discussion of Le Corbusier's human scale in Ching, 2007, p.318). But they are not self-similar; they are more self-same. Simple repetition creates monotony, while self-similarity leads to variations while retaining overall integrity. However, this criterion alone is not enough to create a fractal space.

Criterion 3 – Fractality (the degree of physical complexity): Chapter Three suggested that fractal shapes show higher geometrical dimensions than straight lines and pure shapes in Euclidian geometry. A fractal shape does not lose its complexity when perceived at closer distances (e.g. the Robie house, figure 4.2). However, some seemingly complex forms demonstrate flatness if observed at smaller scales (e.g. Federation Square, figure 4.19). Fractality is, of course, a matter of extent. One fractal shape may exhibit a higher level of complexity than another. Therefore, the calculation of fractal dimension provides the most legitimate and accurate method for assessing the degree of physical complexity (fractality) of an object. It can be measured by one of the methods introduced in the previous chapter (see also appendix B).

Criterion 4 – Hierarchies of connections: There is a rank-size distribution in fractal objects in which large elements are less in numbers as compared to small elements but are more complex as formed by the combination of sub-elements (see Salingaros 1999, 2005; Chen and Zhou, 2004). The complementary elements of roughly the same size are coupled strongly to form an element of the next-higher size. In this sense, in a fractal object, hierarchy is a power law relationship between elements with different sizes, which creates the whole. Batty and Longley state that:

> 'Hierarchies generate power laws and that power laws are one of the bases of fractal geometry' (Batty and Longley, 1994, p.52).

Different types of connections tie elements of different sizes together, so that every element is linked to every other element. The stronger connections are local (close range) ones. Connections might also be between internal sub-elements of distinct groups, but they might be weaker than the elements in one group. Figure 4.22 illustrates two types of hierarchy, a tree-like pattern and a semi-lattice pattern. The latter generates power law relationships which usually occur in complex fractal patterns (see also section 3.2.2.11, figures 3.12, 3.13).

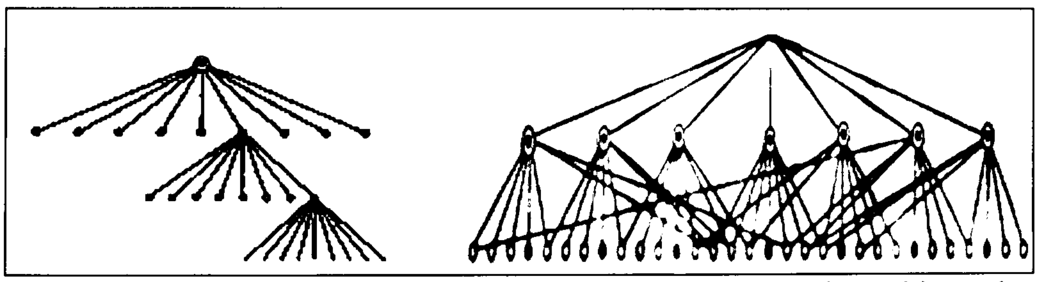

Figure 4.22: The tree like (left) and semi-lattice (right) hierarchies. The latter occurs in complex patterns. (Alexander, 1965; the figure reproduced in Batty and Longley, pp.53-54)

Alexander's (2002a, p.151) property of "strong centres", and Ruskin's (1903, vol.15, p.164) "law of principality" also imply the importance of hierarchical relationships. Both advise that designers should arrange their material so that one element would be more important than the rest, and that the others would group with it in subordinate positions. Thus, in order to conceive the coherence and the congruence of any design, the structural hierarchy of its components must be clear and correspond with that of the whole object in the eyes of the viewers according to the multi levels of conditions and the circumstances of magnification (changing the scale).

Criterion 5 – Change over time/space: Changing character and size can be seen in many fractals. According to Ruskin (1903, vol.15, p. 171), 'if there is no change at all in the shape or size of the objects, there is no continuity; there is only repetition. It is only the change in shape which suggests the idea of their being individually free... from the law that rules them, and yet submitting to it'. Crompton (2002, p.457) referred to Ruskin's (1903) rules of composition and stated that it is the essence of a fractal that it cannot be simply periodic. The simple formal repetition results in an array of self-sameness while the small changes create self-similarity/self-affinity.

The processes of creating a fractal object accept change over both space and time. The change over space in a fractal architecture means that the designer provides the observer who explores the building from inside and outside with a variety of perspectives. In other words, 'elements of e.g. a façade – columns, capitals, base, architraves etc – can be grouped in a way that there is more than one equivalent interpretation presented to the observer' (Meiss, 1991, p.45). An example of this quality can be found in the Eurhythmics Center designed by Enric Miralles (figure 4.23, right); the resulting sections reveal a sequence of varying perspectives as one walks from section A to G and H to P.

However, the change over time means the user of the building or, in the case of a city, the people who use the city space, can change some parts of the original design in order to adapt it to new needs (see also unfolding property suggested by Alexander, 2002b, pp.300-322, 400-401). Time has an important role in the degree of complexity that a building or an urban space demonstrates. Having referred to Victor Hugo's statement, "Time is the architect", Jencks (1997, p.74) wrote that that the details which were added over time would give 'organizational depth' to that space.

In Chartres Cathedral, for instance, change was allowed after two destructions by fire, which is very obvious in its two spires; one belongs to the Romanesque period and the other was built later in the Gothic style (figure 4.23, left). Furthermore, the cathedral was not built in a day; it took one hundred and fifty years of concentrated passion of many building campaigns to create layers of details at the building's different scales. More examples can be found in places that were renovated or even converted to adopt new functions. In fact, if a building or an urban place can adapt to a new situation and can serve many different purposes over time, it lives more, and thus contributes to its sustainability – (see also the quality of "robustness" in urban design terms; Bentley *et al*, 1985). If not, it will inevitably die after a few years of use.

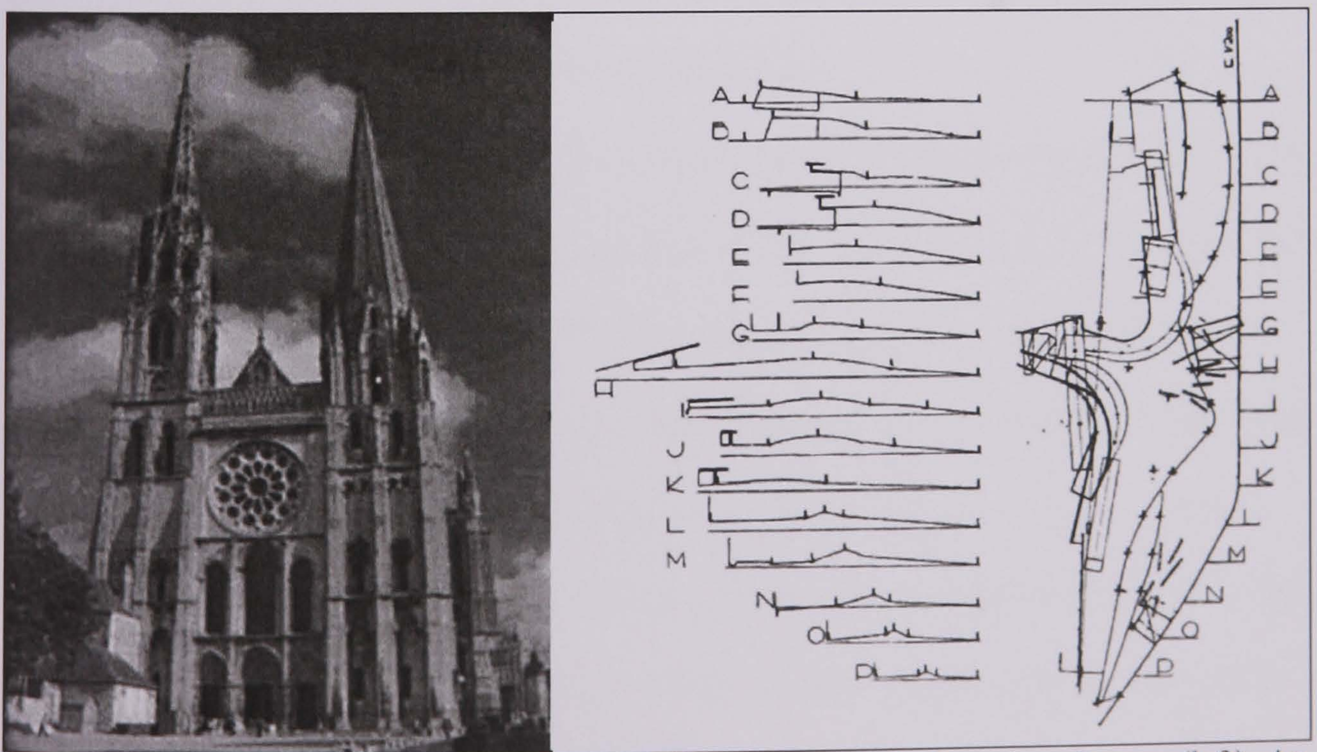

Figure 4.23: An example of change over time, Chartres Cathedral's spires, France (left). An example of change over space, the plan, and sections of Eurhythmics Center, Alicante, Spain, designed by Enric Miralles (right). (Left, Bony, 1983, p.97; Right, Jencks, 1997, p.174)

To sum up, it can be claimed that a piece of architecture or an urban space can be evaluated as fractal, if its fractal dimensions remain high at different scales of observation and the components of its hierarchical structure obtain more if not all of these features: "integrity and multiplicity", "self-similarity", "hierarchies of connections", and "change over time/space". To maintain the focus, this research will not go beyond this point. Further research would be needed to explore the idea of fractal architecture to make valid evaluations possible.

4.2 Part Two: Fractal City; Applications of Fractals and Complexity Theory in Urban Planning and Design

The first part of this chapter discussed the applications of fractals and complexity theory in the field of architecture. The literature related to the theory of fractal cities will now be reviewed. The literature review revealed three themes in which the applications of the complexity theory could be identified: a) conceptualizing city complexity, b) simulating city complexity, and c) measuring city complexity. Reviewing all of these in detail is beyond the focus of this research. However, it is essential to explore briefly each of these themes in order to understand the nature of urban evolution, in terms of the title of this thesis.

Therefore, this part comprises three main sections. In the first section, complexity in planning and design is conceptualised by highlighting the essence of the transition from conventional planning (top down land-use policy and planning) to complex systems planning (bottom up fractal base planning). The weaknesses of traditional planning approaches in the 20th century will be outlined to show how the new views based on complexity theory may change the way we plan and design our cities. Later in this part, the core idea behind fractal cities will be discussed as applied in city simulation and urban measurement. The second section introduces some basic simulation models, and the third section will focus on measuring urban complexity as it contributes to the empirical stage of this research.

4.2.1 Conceptualizing city complexity

In chapter two, the failures of conventional (Euclidian) geometry in analyzing city form and change were discussed. By identifying the features of complexity and their analogues to urban systems in chapter three, it was argued that cities should be viewed as complex systems. In this section, the literature will be reviewed to argue that conventional theories in planning and design have failed to understand the complex nature of cities, and therefore, the methods taken from such views and implemented in practice today have also failed to achieve their goals in predicting and controlling effectively urban shapes and behaviours.

Mashhoudi (2007, p.55) argues that humankind's efforts through history in designing new urban settlements have always raised a significant question. "How can one person or a group of people control the change or decide on the shape of a city that is supposed to accommodate numerous people with a wide variety of activities for a long time, while having an efficient system?" According to Shane (2005, p.305):

> 'The belief that one person can control a whole city or urban situation, marks a crucial difference between Modernist designers (who affirmed it) and postmodernist designers (who do not).... The attempts of the structuralist and rationalist designers to construct a language of urban architecture that included all the traditional elements of the city as a Newtonian clock coordinating the universe by simple laws – all organized around an unanswered question of control.'

The utopian blueprints prescribed in the last century to encompass the distinct features of societies in order to control urban change have been the main goal of contemporary master planners. Cilliers (1998, p.112) who also rejects the validity of utopian approaches, states that:

> 'Whether or not we are happy with calling the times we live in 'postmodern', there is no denying that the world we live in is complex and we have to confront this complexity if we are to survive, and, perhaps, even prosper. The traditional (or modern) way of confronting complexity was to find a secure point of reference that could serve as foundation, a passe-partout, a master key from which everything else could be derived. Whatever that point of reference might be – a transcendental world of perfect ideas, the radically sceptic mind, the phenomenological subject'.

Cilliers (1998) believes that following such a strategy constitutes an avoidance of complexity. In fact, the obsession to find one essential truth blinds us to the bottom up self-organising nature of complexity. The core discussion here is that the notion of a "top down controller" is simply impossible given the degree of complexity that modern cities manifest, and thus any successful control must probably operate from the bottom up. The chief consequence of this bottom up revelation, according to Shane (2005, p.305), is that there will be 'no longer a place for a master plan or a master planner'.

Jacobs (1961) is one of the first theorists who attacked modernist city planning and its solutions in which idealistic orders of blueprints are prescribed. She argued that this kind of planning, which treated the city as a machine, could not handle the nature of the city as "organized complexity". Even 45 years after Jacobs wrote '*The Death and Life of Great American Cities*', it remains the classic book on how urban planners and their linear simplistic models have destroyed functioning cities. It is widely known for its incisive treatment of those who would tear down functioning neighbourhoods and destroy the lives and livelihoods of people for the sake of groundless but intellectually appealing modernistic utopian ideas. Shane (2005, p.307) argues that 'even Lynch (1981), who was critical of modernism, retained the modernist planners' overview, drawing beautiful sketches of views from 30,000 feet and helping by his diagrams eradicate Boston's red-light district in Scollay Square'. The modernists' notion of "top down land use planning" and their "linear-equilibrium urban models" still dominate city planning in practice (see Batty, 2007; Verburg *et al,* 2004; Briassoulis, 2008; Byrne, 2005).

The idea of controlling city changes through deterministic and top down oriented plans was the modernist planners' solution for the poor living conditions of the industrial cities of the 19th century. In the last century, the science of planning responded to city problems through two major transitions (table 4.4). In the first half of the 20th century, the prominent view was of the "City as a Machine" (the first transition) and the prevailing view in the second half was of the "City as a System" (the second transition). In the following sections, these two transitions should be addressed in order to highlight the failure of top down planning approaches. It will then be discussed how the science of complexity can make the third transition in terms of bottom up complex systems planning (see also table 4.1, the sections related to planning at regional and city scales).

Planning in Transition	Transition 1	Transition 2	Transition 3
	City as Machine	City as System	City as Complex System
1900s-1950s	Howard (1989, 1902) Geddes (1915) Jeanneret – Le Corbusier (1929) Bauer (1934) Mumford (1938) Stein (1951)		
1960s-1980s	Osborn *et al* (1965)	Lynch (1960,1981) Crane (1966, 1977) McLoughlin (1969) Chadwick (1971) Faludi (1972) Dennis (1970, 1972) Davies (1972)	Jacobs (1961) Alexander (1977, 1987) Chadwick (1977) Batty (1985)
1990s-2000s			Alexander (2002, 2004) Batty *et al* (1991, 1992, 1994, 1995, 1999, 2005, 2007, 2008) Byrne (1998, 2001, 2003, 2005) Briassoulis (2000, 2008) Cooper (2000, 2003, 2005, 2008) Cilliers (1998) Hamdi (2004) Healey (1997, 2003) Marshall (2009) Mashhoudi (2007) Portugali (2000) Wilson (2000)

Table 4.4: Planning transitions in the 20th and 21st centuries and some key references of each period.

4.2.1.1 Transitions in urban planning and design

4.2.1.1.1 <u>City as a Machine - Planning transition I</u>:

> 'The city as a machine can grow, and it can do so in generally predictable directions and in large, mechanical increments' (Shane, 2005, p.46).

From the early years of the twentieth century, the trend of urban planning (particularly in the UK and US) was towards comprehensive plans with certainty, under the influence of pioneers such as Ebenezer Howard and Sir Patrick Geddes (Hall. The proposition of the utopian concept of the "Garden City" was, in fact, a reaction to the poor living conditions of industrial cities in the 19th century. Byrne (1998, pp.141-142) states that the blueprint suggested by Howard was based on the idea that 'land use planning was an effective mechanism for achieving physical health through separation of people from pollution, a notion of considerable contemporary relevance in the late 20th century'. Based on Howard's (1898) idea, the growth of a metropolis (e.g. London) should be halted by repopulating the countryside and building self-sufficient settlements around the main city. 'These settlements were to have much open space; their economic and social structures were to be controlled' (Larkham, 1991, p.42). They were to be connected by tramway and high-speed train systems, and the location and the size of every land use were to be determined such as:

- Industry, schools, housing, greens, etc – each in its own allocated areas as planned
- Commercial, club, and cultural places – usually in centre(s)

According to the theory of the garden city, each of these small towns was to be of a certain size encircled with a belt of green agriculture. The green belt was to be managed to prevent it from ever becoming urbanised. The town, in its totality, was to be permanently controlled and protected by the public authority to prevent speculation or supposedly irrational changes in land-use, population, density, and size – the maximum population, for instance, was to be held to 32,000 and 58,000 inhabitants for each of the small towns and the central older city respectively (see Osborn and Mumford, 1965). Geddes (1915) extended Howard's concept to the planning of whole regions. Under such regional planning, garden cities would be rationally distributed throughout large territories, merging with natural resources, balanced against agriculture and woodland, forming one logical whole (Welter, 2002).

The ideas of Howard and Geddes were followed by many planners and designers during 1920s and afterwards, such as Lewis Mumford, Clarence Stein, Henry Wright, and Catherine Bauer. Even planners with no particular interest in the idea of the garden city were intellectually governed by underlying principles of the garden city (Jacobs, 1961). The most radical mechanistic idea of city planning was suggested by Le Corbusier in the 1920s. In his dream city, the Radiant City, he proposed a vertical version of a Garden City, an idea of skyscrapers and super-blocks within a great park (figure 4.24). In Le Corbusier's vertical city, all social and spatial elements were determined: 1200 inhabitants per acre, the land occupied by high density skyscrapers mainly accommodating low-income people, high-income people would be in lower, luxury housing around courts, and the ground level left for restaurants and theatres, etc. Most of the ground could remain open for green space and transportation including great arterial roads for express one-way traffic.

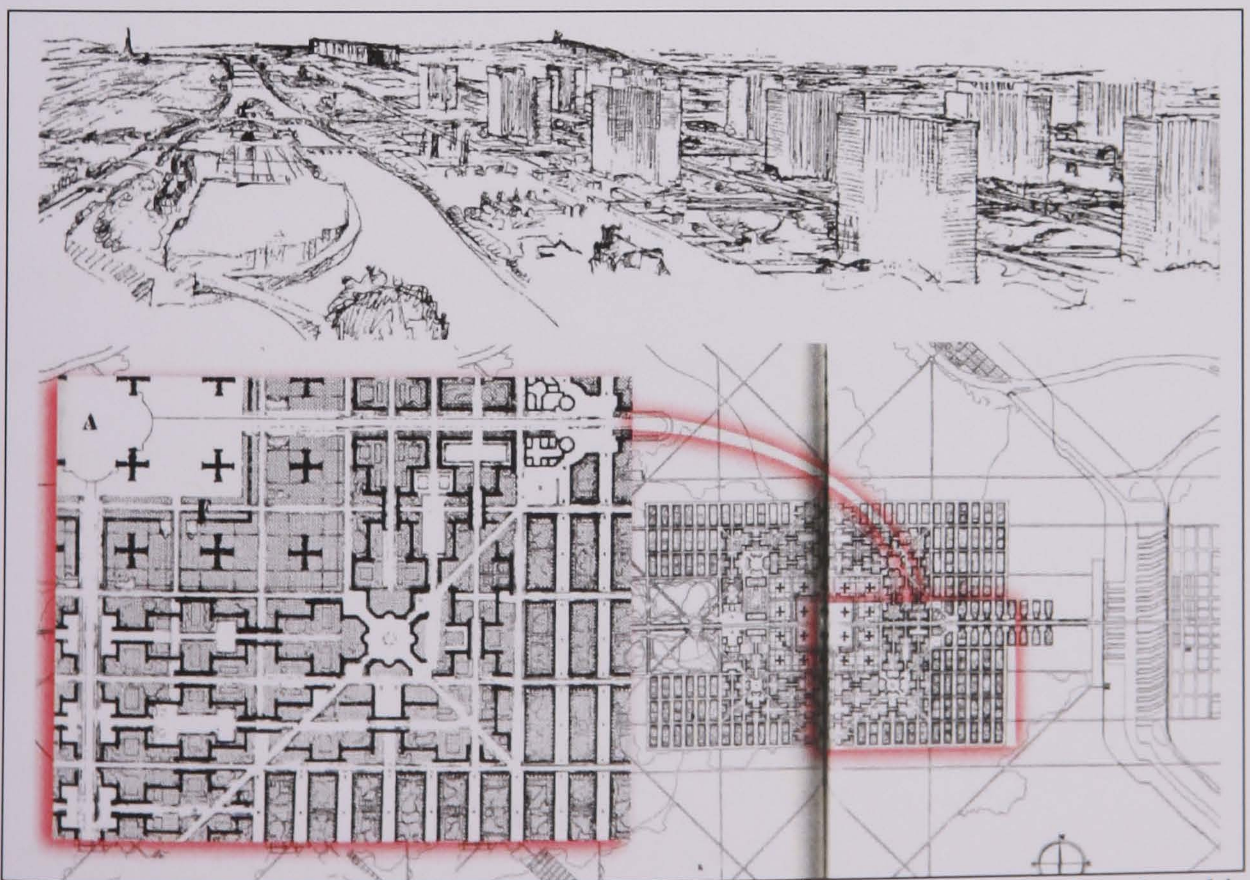

Figure 4.24: The sketch for the centre of Paris proposed by Le Corbusier based on his theory of the Radiant City. (Jeanneret, 1929, pp.174, 175, 200, 280)

Jacobs (1961) claimed that up to the mid-20th century, an increasing number of housing reformers, zoning planners, highway planners, legislators, land-use planners, and modernist architects popularised such simple mechanistic and easily comprehensible ideas of super-blocks, project neighbourhoods, and the unchangeable plan. The result, in fact, was 'anti city planning', she argued:

> 'the mechanistic way in which cities were conceived and planned was entirely counter to the diversity that made up vibrant and living cities, with the result that post-war urban planning (and modern architecture) were killing the heterogeneity and diversity that characterized urban life' (Jacobs, 1961, pp.21-22, also quoted in Batty, 2007, p.7).

It was, in fact, a mechanistic and Laplacian version of urban planning in which the future would be predicted and determined if comprehensive research was undertaken on the past and the present. Batty (2007) referred to Jacobs' statements and marked the failure of such superficial mechanistic view of modernist planners. He pointed out, 'In the mid-20th century, the prevailing view of society was one which treated social structure akin to the way machines functioned... the metaphor of the city as a machine ignored self-determination and was only barely applicable in the most cursory ways to social problems' (Batty, 2007, pp.3-7). Norman Mailer described the image of American cities in the early 1960s as: 'the runway destruction and development creating empty landscapes of psychosis' (quoted in Jencks, 1997, p.77).

4.2.1.1.2 <u>City as System - planning transition II</u>:

Before the mid-20th century, it was believed that the city must be designed in a specific area and its future expansion must be controlled. With the influence of systems theory in the 1960s, predicting the growth and change in activities of cities as the main intention of traditional urban plans became obsolete. The concept of dynamic systems theory motivated planners to revise traditional urban planning. In Britain, for example, 'the approach sustained by developments in planning theory and method was popularised in various texts such as McLoughlin's (1969) *Urban and Regional Planning: A System Approach,* Chadwick's (1971) *A Systems View of Planning,* Faludi's (1972) *Planning Theory* and so on' (Batty, 2007, p.7).

The systems approach can be considered as the second transition in planning in the 20th century. The former methods – in which master plans, with their architectural projects were fixed – were replaced by "plans with policies" to provide more flexibility to the way in which cities were developed in the future. Byrne (1998) marked this as an important, logical, and practical progress in planning:

> 'The move in the post-Second War period towards a system conception of planning, embodied in the UK's planning system by a shift from "map-based land use" planning to the "document-founded structure plans", was a perfectly logical development of planning as practice' (Byrne, 1998, p.142).

The aim of designing new cities was to create a system that would easily encompass all the activities of numerous people, while having the power to be flexible in favour of the dynamic concept of a city. New issues such as structural theories and systems theories contributed to the understanding of the city as a system in a new way, where numerous subsystems interact to create the whole. Based on this view, urban design and planning were aimed at predicting the structure of a city that could accept growth and change. A revision in size and capacity can be seen in the cities designed after the Second World War - especially in the UK (see Larkham, 1997, 2003, 2008). 'In designing the new city of Milton Keynes with a free-economic system, the goal was to create a structure with the maximum capability for flexibility and development', and 'the designers of Islam Abad and Saadat city followed this aim too' (Mashhoudi, 2007, p.56).

According to systems planning, the city was no longer viewed as a simple element with a clear definition. In designing a city, a system was discussed as being flexible, expansible and without former traditional limits. Thus the structural approach to systems discarded the method, which took the city to be complete and outlined every element. This new view of the city inevitably changed the principle of urban planning and how goals must be achieved. Design and change in this view should obey a hierarchical structure. Therefore, planners set up some priorities in order to maintain and enhance the main structure of the city and to develop other parts in more flexible but still in a coherent way according to the whole structure.

In 1977, 'David Crane proposed that urban designers and planners priority should be to create first the public element of a city (the element in which the public sector will invest). These elements and the factors that are controlled by the public sector, will then guide the activities and the factors of the private sector, which stand at a lower hierarchical level' (Mashhoudi, 2007, p.57). This made the distinction among elements that play a structural role in the city. The goal was to define a systematic and hierarchical relationship among structural elements by which any change or evolution in any other element of the city is to correspond to the construction of whole system structures and become harmonious with the main structure.

4.2.1.1.3 Advantages and limitations of systems planning:

Indeed, as soon as the systems approach was articulated, its limits became evident – in both the spatial and social urban aspects. From the social point of view, it ignored the rationality which interpreted working-class action (local) as the basis for the universal progress in a city (global). Byrne (1998) argued that despite systems planning claiming to assert value neutrality, in practice it served capitalist development interests – those involved in the construction and development industries. From the spatial point of view, this approach thinks of cities as systems in "equilibrium" with planning aimed at maintaining this equilibrium (Chadwick, 1971). This clearly conflicted with innovation, competition, conflict, diversity and heterogeneity; all hallmarks of successful democratic city life which led us to the new paradigm of "complexity theory" (Batty, 2007).

In theory, planners as engineers were aware of the potential of systems theory; however, in practice, they usually took up more simplistic and linear models of the systemic approach where they were generally incapable of directing spatial understanding and social evidence in the formation of objectives. According to Batty (2007), casting most urban problems into such narrowly defined domains was simply not sensible and feasible, and much of our understanding and their planning remained beyond the systems approach.

> 'Intellectually too, it was clear that what had emerged was a rather narrow view of the way systems behaved: most systems were not in quiet and passive equilibrium but in turmoil much of the time while the idea of evolution to new conditions implying different structures and behaviours was simply beyond this kind of thinking' (Batty, 2007, p.7).

However, the system-based structure planning process was not a disaster as it had a representative democratic element, a considerable element of public consultation, if not participation (see Dennis 1970, 1972; and Davies, 1972). 'The planning disasters, which played an important part in the discrediting of planning as part of collective intervention, were largely the work of simplistic architects and road engineers, both in partnership with civil engineering capital' (Byrne, 1998, pp.142-143, see also Hall, 1980). In summary, the main advantages and limitations of systems planning can be outlined as:

- It demonstrated some democratic elements in terms of public consultation – but not public participation.
- It considered the free interaction of subsystems generating flexible local forms as private elements – but only within a hierarchical framework of relationships with the public elements as the main structure of an urban system, in which their positions should be predetermined.
- It revised fixed land use-based master plans to more flexible policy-based master plans – but still through the top down view with predictable outcomes, trying to keep the system in equilibrium (within certain targets).

In designing a city, a system was discussed as being flexible, expansible and without former traditional limits. In this sense, it can be claimed that the systems approach was a more realistic version of master planning. Nevertheless, its overall view remains the same following top down deterministic logic.

4.2.1.1.4 Planning in the conventional top down approach:

In fact, from the Renaissance to the Modern Era, rationalism and utopian ideas have been dominant (Cilliers, 1998). The idea that urban form and function could be 'controlled' and 'planned' to meet certain goals and targets was a natural extension of such logic. Absolutism of modern science and the persistence of rationalists and structuralists in obtaining a certain, definite, and the unchangeable image for the laws of existence became the base for studying the city in the 20th century. The most common fact in mechanical rationalism (the first transition) and systematic structuralism (the second transition) is that both have a top down routine.

The city planners of the 20th century tried to imagine conversation between urban factors from a top down perspective and to create overall structures to serve local actors' needs. The top down routine sometimes has political expediency – particularly in developing countries. In such cases, the plan will not have a practical purpose; hence obviously it does not serve local actors' need at all. However, even in the cases where top down planning follows practical purposes, mostly it cannot satisfy the ground problems at local level. It can be claimed that the conventional planning is a long process short on product, despite the demand from most poor people for the opposite (see Byrne, 2003; and Hamdi, 2004). That is one of the fundamental problems of top down master planning. The following example given by Hamdi (2004) describes what is usually happening in conventional planning practice:

> '...somewhere along the way a few projects will have got started – some housing will have been built, a road, a clinic, an upgrading project or two or an outmoded sites and service project – but not enough to make a real difference because, by the time you have done all planning and thinking, you will have probably run out of money anyway for the doing. In any case, in the time it has all taken, the government will have changed, the international /national focus will have moved on to some other new agenda of priorities, the cease fire amongst warning factions will have been called off and your favourite mayor will have been moved on or been displaced. And probably, in the time it has all taken, the problem on the ground at local scale will have changed or disappeared or managed by local people in their desperation, and other problems will have appeared. Local problems and issues will, therefore, be reshuffled and redefined to fit the strategy plan which, by this time, will be too expensive or too difficult to change' (Hamdi, 2004, p.104).

After all, if master planning, in its conventional top down routine, is not working properly, then, the principal question is "where is planning best placed?" (Hamdi, 2004)

In chapter three, it was concluded that cities demonstrate the characteristics of complexity, and therefore, they are to be studied and treated as complex systems. Batty (2007), Briassoulis (2008), and Byrne (2003) clearly state that a clear planning transition is taking place away from classical thinking (positivism, reductionism, linear and static worldviews) towards complex systems thinking (alternative epistemologies, holism, nonlinear, and dynamic worldviews, which are all the hallmarks of complexity theory). In fact, this is 'the concentrated action of millions of individuals and agencies that generate structures of complexity that are virtually impossible to manage, control or redesign from the top down' (Batty, 2007, pp.3-4).

4.2.1.2 City as complex system (planning transition III)

> Cities should be identified, understood, and treated neither like simple mechanical systems nor like disorganised complex systems, but as 'organized complexity' (Jacobs 1961, p.434).

From the two earlier transitions, urban planning, as a science, has been significantly developed to serve many aspects of city life. However, it has not yet coped with the uncertainty and intrinsic complexity of the city system. Despite the recent theoretical developments in understanding of urban complexity, the linear top down planning approach with absolute authority over the time-place dimensions – inherited from the last century – is still dominant in practice. This approach would reduce the complexity and dynamics of the urban systems to a series of "static slides" designed once with certainty (certain targets), and this would be far from the fact that cities are not systems in equilibrium (Bak and Sneppen, 1993; Bak, 1996).

Planning practice, therefore, calls for another transition responding to the dynamics of the complex city system. The third transition suggests that views of planning must change from the city whose physical form and function can be determined, designed and manipulated (the city system in equilibrium) to the city whose temporal and spatial characteristics is far from equilibrium (the city system in fragile equilibrium). 'This is a switch from thinking of cities as being artefacts to be designed to thinking of them as systems that evolve, that grow and change in ways that might be steered and managed but rarely designed from the top down' (Batty, 2007, p.3).

4.2.1.2.1 Planning as a complex bottom up approach:

> '[cities] are to be viewed and manipulated like a living systems with the implication that life, hence city form, emerges from the bottom up following the Darwinian paradigm of evolution' (Batty, 2007, p.9).

Since the late 1980s, there has been a growing trend towards complex systems planning (see table 4.4) suggesting a radical shift from top down and centralized structures of government and management to much more decentralized organizations (see in particular, Batty, 2005, 2007, 2008; Byrne, 2001, 2005; Briassoulis, 2000, 2008; Healey, 1997, 2003). These writers suppose that effective actions and decisions come from the individuals and agents who respond to their environment and each other, competitively and collaboratively from the bottom up. Therefore, urban planners and designers have been advised to shift their focus from top down control to bottom up. The main challenge, however, is "how?"

There are two views about how such a shift should be applied to planning. While the radical approach is based on a complete abandonment of top down control, the moderate approach suggests an active planning, somewhere between the bottom up and top down processes of decision-making. Nevertheless, both approaches follow very similar principles, but with a different emphasis. While the first group emphasizes chaos theory and transitions from order to emergent chaos (e.g. Cartwright, 1991; Byrne, 1998, 2003; Shane, 2005), the second group emphasizes complexity theory and the importance of transitions from chaos to complex order (e.g. Cilliers, 1998; Hamdi, 2004; Batty 2005, 2007; Mashhoudi, 2007).

The first group of proponents of the complexity theory deny the validity of comprehensive approaches in terms of master planning or other authoritarian centralisms and instead emphasized on a kind of 'incrementalism' as the only appropriate planning approach. In fact, This first group reject the need for an overall control in terms of 'master plans' in a belief that cities are to be controlled only through the bottom up logic. Cartwright (1991) and Shane (2005) showed such a belief in the following statements:

> 'With hindsight, we can see the post-structuralist and deconstructivists were right to describe the city as a chaotic situation of competing systems.... The chief consequence of this revelation was that there was no longer a place for a master plan or a master planner. The complexity of city's various autonomous systems, each with its own logic, meant that nobody could coordinate everything' (Shane, 2005, p.305).

> 'On an incremental or local basis, the effects of feedback from one time period to another are perfectly clear. This is a powerful argument for planning strategies that are incremental rather than comprehensive in scope and that rely on a capacity for adaptation rather than on blueprints of results' (Cartwright, 1991, p.54).

To incrementalists, planning will have been calling for "public participating", "self-regulating", and "self-policing" strategies, which are emerging from bottom up processes, resulting in a flexible matrix of possibilities to operate without central control. David

Byrne, who has investigated the application of complexity theory in social engineering an urban system, proposed a complex-based social model in which the collective agency of free citizens as 'the proper actor of democratic modernity' chooses a future that would be formed from the range of possibilities that might be. He wrote that:

> 'An engineering of bottom up process applied to social sciences is based on understanding of how things became as they are and simulation of how they might be in the future' (Byrne, 1998, p.167).

According to Byrne (1998, p.143), 'The condition space defines possibilities – the plural is crucial – planning is about which outcome is achieved…. This method is about alternatives; about different way in which things might be done in order that different sorts of futures might come into being. The following statements from Shane (2005) and Byrne (1998) show where this kind of approach to complex system planning may take us.

> The important thing about planning is that it is about choices and the important thing about chaos/complexity programme in relation to planning is that it provides a rational framework, which is not based on simplistic determinism but rather is explicitly founded on reflexive social action. …what is interesting is that a chaos/complexity perspective on the governance of cities suggests that mass participatory processes are not only morally preferable but actually represent the only process through which the achievement of unificational non-divisive urban forms may be possible…. It is perhaps where complex general system might take us – a decent sort of utopia after all' (Byrne, 1998, pp.142-143).

> 'We can also see that this chaotic situation has an emergent logic of its own, produced non-centrally by actors designing systems across vast territories without regard for other's decisions, each adding their own system as a new layer to existing topography, historic structures, and landscapes…. Each actor follows their own logic, creating a life-world that is a mixture of the usual urban concerns: land and property, trade and market share, social and political position. Each actor forms their own hybrid priorities and sets goals in the face of competing actors, contesting for territory' (Shane, 2005, p.306).

From this point of view, developments take place by successive and often incremental adjustments, and therefore, only bottom up control makes logical sense. They argue that local and global actors on the ground meanwhile create independent lines of communication using their own logics, unimaginable by large-scale plans. While the view of this group asserts the bottom up planning process of competing actors as the only possible and valid approach, there is also another view on the implication of complexity theory for planning in which the need for overall top down controls is not completely rejected.

The second group join with the first in rejecting the validity of top down conventional master planning and focusing on the bottom up. However, while the first group claims that the higher controls do not have any function, the second group believe that the control from the top down and bottom up should be considered side by side – with the emphasis on the latter. According to the second group, controls, whether local or global, are not to be imposed by the blueprints of a planner or a group of planners but from the bottom up through hierarchical control systems of individuals, groups, local communities, institutions, organizations, and governments.

> 'No one would pretend that cities and societies only grow in competitive and uncoordinated fashion from the bottom up for individuals act in groups, they form institutions with governments of various kinds acting in top down fashion but at different levels.... Complexity theory just changes the focus from top down to bottom up, but with structure and order emerging as much, if not more, from the bottom up' (Batty, 2007, p.4).

The supporters of the second view admit that actions for planning and developments must be taken at both local and global levels. However, they believe that this requires a hierarchy of levels of control in which some sort of top down and bottom up processes interact in a feedback loop to control and facilitate the process of change in city. 'There is a need to drive imperative of rights, to connect practical work with strategic work, freedom with order, small-scale organizations with large-scale organizations, top down coordination, and bottom up design' (Hamdi, 2004, p.93). This view recognizes the need for both opposites, not one or the other alone.

4.2.1.2.2 Conceptual complex planning models:

The conceptual complex planning models call for the features that constitute the city as complex system. In Chapter Three, the characteristics of complex systems and their analogies to this urban system were identified, including "Deterministic Chaos", "Feedback", "Sensitivity to Initial Condition", "Limited Predictability", "Emergence", Self-organization", "Adaptability", "Hierarchy and Levels of Scales" and "Fractal Generated Patterns". Any constructive attempts to apply complexity theory to planning and design have to acknowledge and incorporate these features not as epiphenomena, but as the constitutive elements of complex systems. These features are central to any complex urban modelling in its all related fields from physical/human geography, socio-economic studies to planning and urban design. Hamdi (2004) and Mashhoudi (2007) propose two conceptual planning models (Action Plan and Fluid Plan respectively) that define the role of planning in a way that serves both local and global actors. What follows is a summary of these two models.

a) Action plan:

The planning model suggested by Hamdi (2004) defines the planning role where it can serve both local and global actors in a cycle of a top down and bottom up process as opposed to the conventional planning model with only a top down approach (figure 4.25).

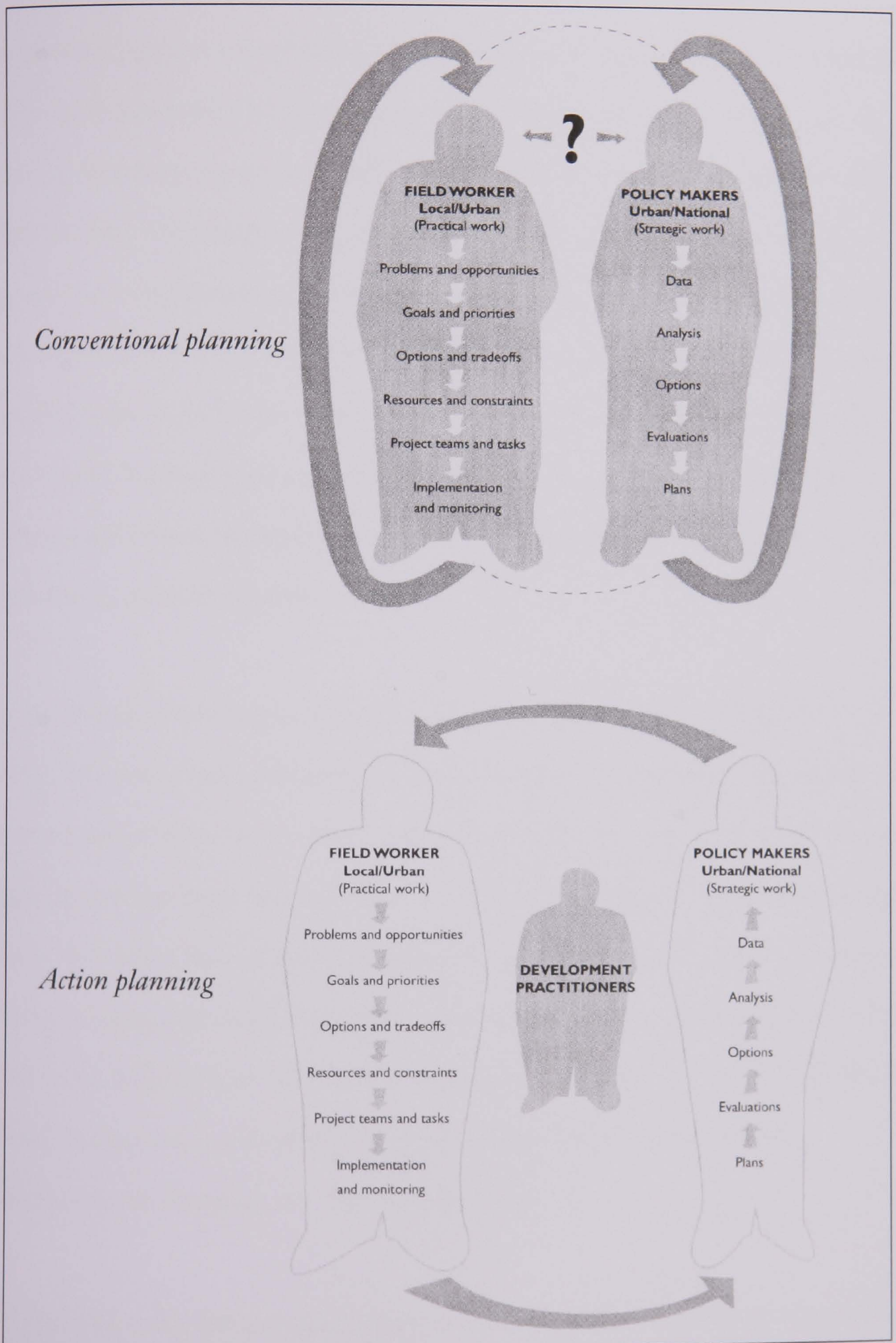

Figure 4.25: Above, the conventional planning; top down process of a number of decision makings which leads to conflict when it comes to implementation at local level. Below, the action planning; a balanced process of decision making from bottom up together with top down in which national and local processes control each other. (Hamdi, 2004, p.102)

In figure 4.25 (above) Hamdi shows the routine in conventional planning. As illustrated, following data collection and analyzing existing situation, objectives and priorities are set based on what planning deems necessary or desirable, or both, in the national or even global interest. The strategic plans then will be set up by a series of policies. It can be assumed that if good policies are made, good programmes will somehow follow. these policies aim to reflect the local needs. Then the larger order of structure will be designed first into which projects must fit, denying all the novelty discovered in the community (local scale). Such a process is top down. The relationship between the top and the bottom is awkward at best and is sometimes in stark and open conflict. All this is reinforced by the planning process itself.

Instead, Hamdi (2004) suggested that the order of work can be reversed (figure 4.25, below). The loop of policy planning will then concentrate on problems, opportunities and priorities derived from the ground (Local scale). This will be on the assumption that the bigger picture, the larger order of plan or policy, if it is to serve the interests and needs of people, will derive from all small and successful initiatives going on in the community. 'And so working with local counterparts, starting small and starting where it counts, we build up the larger plan for social enterprise and good governance based on new forms of mutual engagement, a revised policy of land tenure, a spatial structure plan of infrastructure development, etc' (Hamdi, 2004, 105).

The planning model that Hamdi suggested is based on the fact that the larger plan is built up through bottom up processes associated with alternatives. The analysis of each alternative will reveal the gaps in our knowledge, an assessment, and provide a better understanding of what impacts we are likely to achieve, what harm it might do. This may lead us to more targeted data searches or surveys that will better inform our planning about local problems, opportunities and local risks and that, in turn, may demand revisiting our goals and priorities and so on. The process is, therefore cyclical and Hamdi (2004) claims that it is more likely to lead us to a policy environment which is at once connected to issues on the ground and which facilitates emergence (bottom up processes), rather than determine the future.

b) Fluid-plan:

Mashhoudi (2007) also referring to the failure of conventional planning, suggests a conceptual fractal-planning model named the Fluid Planning Model. He claims that his model reflects the city complexity in which:

> 'Firstly, the city will be viewed as a chaotic system with all its resulting features including, emergence, creativity, unpredictability, sensitivity to its initial conditions, etc; and sees disorder and uncertainty as a unique basis for order that stems from the complexities of the environment.
>
> Secondly, the new decisions are constantly made by citizens. Therefore the spatial system will itself receive input of conflictive data which needs interpretation by the system to be accepted as constructive (informative) or to be discharged as destructive (noise).
>
> Thirdly, the role of planners is interpreting the data which is collected from the interaction of individuals and society to recognize them positive or negative feedback. However, the final decision makers are not the planners, but the people. This is only possible by formulating a cognitive framework of subsystems' (Mashhoudi, 2007, pp.61-62).

According to Mashhoudi (2007), a cognitive framework is a semi-topologic scheme of the city in clear layers to understand the qualities in the urban system as potentials for remaking and renewing the organization of the city. This framework can be used as an outlet to facilitate the flow of information between Macro-systems and Micro-systems, in order to have a firm base for planning of the city. The Fluid Plan does not determine the functions and land use of the city; instead, it presents some alternative images for the future of the city, without determining them as final. It allows information to flow between different hierarchical organizations. This increases the divergence of scenarios during planning and interactions' process of subsystems to achieve the optimum time-place situation (choosing the best option at the relevant time and place). Mashhoudi's (2007) model also includes two particular suggestions about urban morphology:

1- Eliminating unrealistic official borders and Euclidian boundaries that separate the areas, district, and regions, instead, drawing a map based on its real morphological qualities.
2- Asserting qualitative/quantitative structural laws as fractals in order to create flexibility as well as composing shapes and forms without imposing a simplistic view (e.g. reductionism) on the innate complexity of the urban environment.

While the systems approach of the late 20th century suggested "public consultation" as part of the planning process, both Hamdi's action-plan and Mashhoudi's fluid-plan emphasise public participation. However, their models are very rough and still at very conceptual level. They did not elaborate how the models might work in practice. Nevertheless, both models certainly demonstrate some of the main features of the complexity approach such as processing data from the bottom up, which are essential for a "constructive realism" – as Mashhoudi (2007, p.59) noted:

> 'The complexity theory signifies the active chaotic urban system as an independent and open organization, opposing to the certainty of utopian views. Hence, "constructive realism" can provide a firm basis for the natural growth of the city and individual and social dynamics.'

4.2.2 Simulating city complexity:

> 'Computer-based simulation modelling, e.g. Cellular Automata (CA), is based on a precise recognition of the non-linear character of city systems. It provides a new systems-founded rationalism in planning as a process' (Wyatt, 1996, p.650).

> In a world where global interventions fuse in subtle and diverse ways with local action, CA (Cellular Automata) looks like a paradigm for the 21st century, resonating with everything from the postmodern mathematics of fractals and chaos to the cry of development theorists 'Think globally, Act locally' (Batty, Couclelis, and Eichen, 1997, pp.160-161).

Since the 1980s a number of different simulation models have been suggested based on the features of complex systems such as CA (e.g. Couclelis, 1985, 1988, 1989; Phipps, 1989; Cecchini and Viola, 1990, 1992; Wu, 1996; Batty *et al,* 1994, 1998, 2005), DLA models (e.g. Kadanoff, 1986; Bunde and Havlin, 1991; Batty *et al,* 1994, 1997, 2005), Correlated Percolation (CP) models (e.g. Makse *et al,* 1995; Peterson, 1996), CAST (Jankovic *et al,* 2005), and so on. The main feature of all simulated urban models is that the algorithms of such models should allow bottom up data processing. The cells are usually conceived as occupying spaces with processes for changing the state of each cell through time and space. This means that data and choices run through by cells, with their positions and relationships, are not determined in advance. Conventional models, however, largely determine the scenarios that involve top down intervention. The other important feature of such simulative models is termed dynamic interaction. Change in one cell cascades across the city to many other cells, largely uncontrolled from outside. In other words, changes in one part of city have an impact on other parts.

The most famous simulation models are known as Cellular Automata (CA) dated back to the very beginnings of digital computing in the early 1950s. Turing (1952) and von Neumann (1966) who pioneered the notion of self-reproducible machines suggested that 'organic development might be susceptible to computation' (Batty, 2005, p.67). Their ideas inspired many computer experts and mathematicians including John Conway (reported in Scientific American by Gardner, 1970) whose model, "Game of Life", combined all notions of CA and simulated the key element of self-reproduction. According to him, life could be modelled on an infinite grid of cells, those which were active or alive being subject to a series of local rules pertaining to the birth of new cells and the death of existing ones.

Conway's Game of Life model was then developed by a number of other researchers. 'Tobler (1979) argued that CA could be applied to geographic investigation, Couclelis (1985, 1988, 1989) has used CA to model spatial dynamics, Phipps (1989), Cecchini and Viola (1990, 1992) have applied CA to a variety of geographic phenomena' (Cooper, 2000, p.136). CA and DLA (Diffusion-Limited Aggregation) are modelled on a grid of cells, which are subject to a series of rules governing the behaviour of each cell in relation to the behaviour of its neighbours. The essence of such modelling consists of the following four distinct principles, as Batty (2005, pp.68-76) states:

1- There are a grid of cells – named by i {i=1, 2, 3,..., N}- representing a spatial or functional character (e.g. building blocks), and manifesting some adjacency or proximity to one another.
2- Each cells can only take one state at any one time – named by Di(t) – from a set of states (D) that define the outcome of the system. (For the most usual and simple 2 dimensional grid case, the cell can take either states of Di(t)=0 or Di(t)=1, indicating whether the cell is dead/empty or alive/occupied respectively).

3- The state of any cell depends on the states and configurations of other cells in the neighbourhood of that cell (named by Ωi), as the immediately "adjacent set of cells" – cells that, in some sense, are nearby or next to the cell in question.

4- Finally, there are transition rules (f) that drive changes of state in each cell as some function of what exists or is happening in the cells' neighbourhood. Then, the most basic mathematical interpretation of such transition rules at any time (t) will be:

$$f[D_k(t) \subset \Omega_i] \rightarrow D_i(t+1) \qquad \text{(equation 4.1)}$$

Through the transition rules (f), the above equation determines temporarily the state of each cell as follows:

a) <u>Death in isolation:</u>

If the cell has less than two active neighbours, then it will become inactive – it will die in isolation.

$$\Sigma\, D_K(t)<2 \rightarrow D_i(t+1)=0 \qquad \text{(equation 4.2)}$$

b) <u>Steady state:</u>

The cell remains alive if there are two or 3 live cells adjacent to it. However, the cell with only two live neighbours is alive but does not give birth, which implies a steady state.

$$\Sigma\, D_K(t)=2 \rightarrow D_i(t+1)=1 \qquad \text{(equation 4.3)}$$

c) <u>Birth–growth:</u>

If there are exactly 3 live neighbours next to the cell in question, that cell is not only alive, but actively gives birth.

$$\Sigma\, D_K(t)=3 \rightarrow D_i(t+1)=1 \qquad \text{(equation 4.4)}$$

d) <u>Death-overcrowding:</u>

If a live cell is surrounded by more than three active neighbours, then it will die from overcrowding. This rule acts as a system feedback which controls the growth (Compare it with feedback in logistic equations 3.2 and 3.3 in chapter 3).

$$\Sigma\, D_K(t)>3 \rightarrow D_i(t+1)=0 \qquad \text{(equation 4.5)}$$

The dynamics of applying the rules can be visualized on a screen within an interface environment provided by a computer program. It is possible to program them in spreadsheets such as Excel, Lotous, Quattro-Pro or within the graphic capability of CAD and GIS software (Wu, 1996). For visualization, pixels represent the cells and they are allowed to accept states (on/off). Different fractal patterns emerge through running programs according the rules given to them.

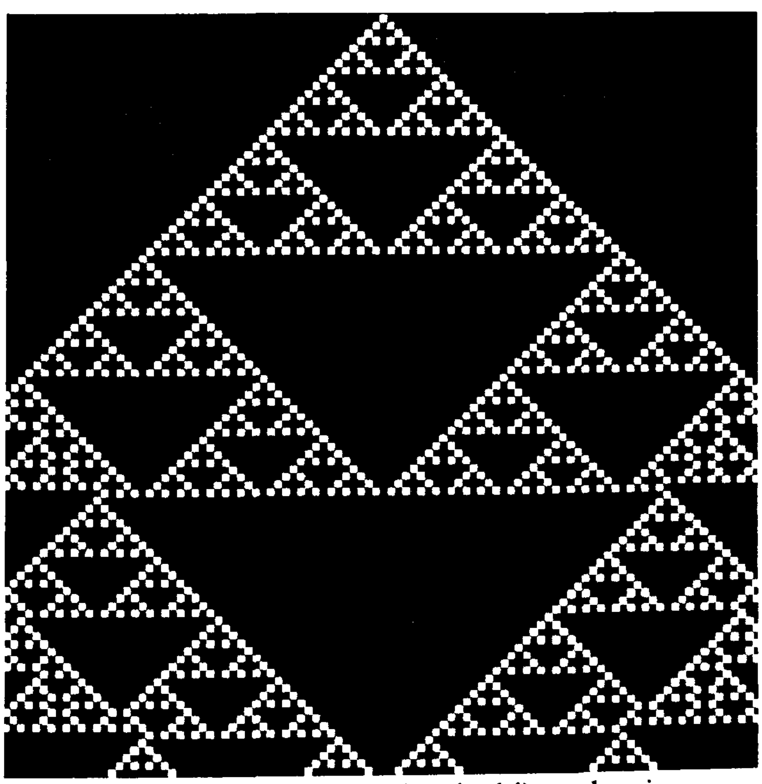

Figure 4.26: Structural (Sierpinski) order in one-dimensional cellular automaton. (Batty, 2005, p.81)

For instance, one of the very basic CA models can be created by using a one dimensional string of cells where K=3 (the number neighbourhoods) and D=2 (the number states), with the central cell as Di=1 and all others equal to zero. This leads to the fractal pattern shown in figure 4.26 known as the Sierpinski triangle (see also figure 3.18 in Chapter Three).

Neighborhood Type	1	2	3	4	5	6	7	8
Configuration	111	110	101	100	011	010	001	000
Transition Rule	0	1	0	1	1	0	1	0

Table 4.5: the rule behind a one-dimensional cellular automaton, known as the Sierpinski triangle. (Batty, 2005, p.80)

An interpretation of the rule leading to this pattern is given in table 4.5: 'For any cell that either "on" or "off", then if there are no other cells "on" in its neighbourhood, the cell is switched off (dying from isolation)... If both the other two neighbours are "on" then the cell also dies from overcrowding. However if one of the cells in its neighbourhood is "on", then the cell either stay "on" – remains on – or is switched on' (Batty, 2005, p.81).

However this very organized fractal pattern with apparent order illustrated in figure 4.27, will behave strangely in which 4 types/classes of dynamics may emerge if the program is run indefinitely within a closed system. Figure 4.27 illustrates these for types as; I) *limit points* or with point attractor; II) periodic structure which recur over fixed *limit cycles* with simple attractor; III) *chaotic patterns* with strange attractor; IV) and highly localized ordered patterns that reveals *complexity*. (Compare the diagram and illustrations in following figure with the Feigenbaum diagram illustrated in figures 3.6 and 3.7 in Chapter Three)

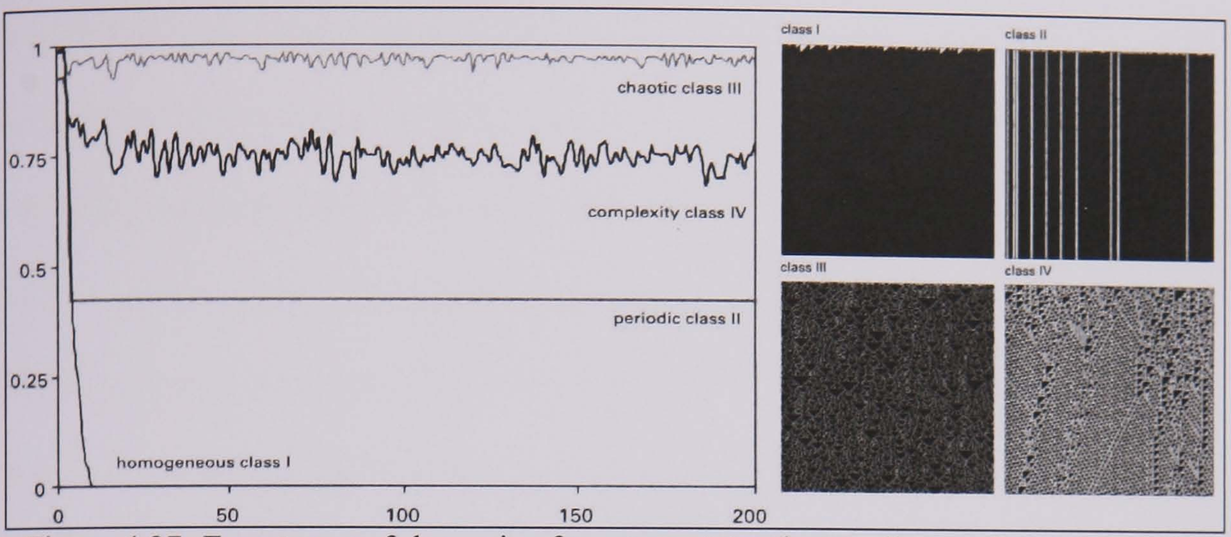

Figure 4.27: Four types of dynamics for a two-state, three cell, one-dimensional CA model. (Batty, p.84)

Diffusion-Limited Aggregation (DLA) models follow similar principles as CA models. DLA technique was suggested first by Witten and Sanders (1981, 1983). It was explored by Batty and Longley (1994) using the technique in greater depth to simulate urban growth. Batty (2005) illustrated its wider potential experimenting with a scaling model of urban form. The experiment of the DLA model involves planting a seed in a central place – at the centre of a two dimensional space (called a lattice) and building up a cluster around this seed by launching particles at some distance far away from the edge of the cluster (figure 4.28, Left). Each particle makes a random walk on the lattice until it reaches a lattice point adjacent to one already occupied by a particle where it sticks, or until it leaves the system by crossing its boundaries where it is deemed to have disappeared or been destroyed.

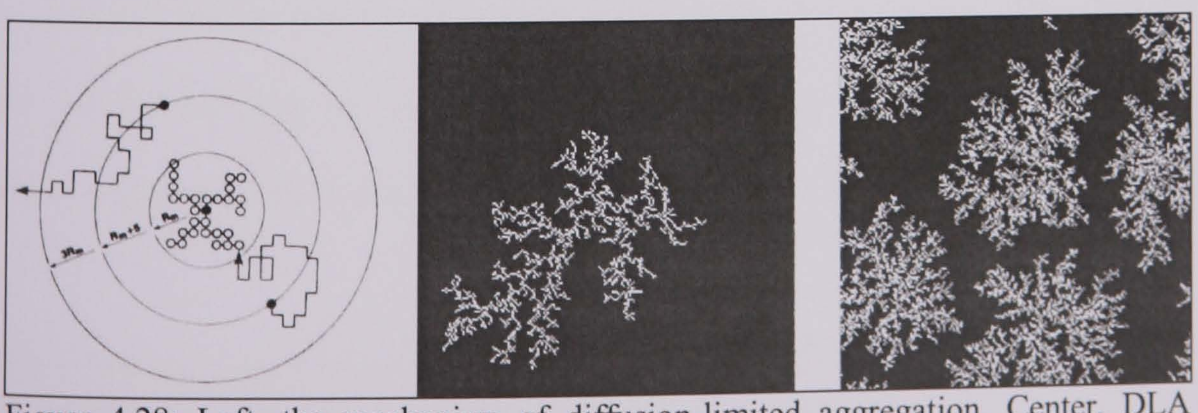
Figure 4.28: Left, the mechanism of diffusion-limited aggregation. Center, DLA cluster developed from one seed. Right, DLA clusters developed from many seeds. (Left, Batty and Longley, 1994, p.255; Right, Batty, 2005, p.130)

Figure 4.28 illustrates the resultant clusters when only one seed or many seeds were developed. The area of the city would expand in proportion to the square of the radius of the cluster(s) developed by one or more seeds. Batty and Longley (1994) argue that DLA is similar – not the same – to a simple urban growth model, where the city grows by individuals locating next to or near individuals who have already clustered about the central point. Although DLA simulations are not identical to real urban structures, their similarities are strong and they can be used as a basis for comparison (Batty and Longley, 1994, p.244).

In summary, DLA models have advantages in presenting the characteristics of a complex organic growth. Their generated structures are familiar tree-like forms grown from the seed, manifesting self-similarity of form across several scales, and whose properties of scaling suggest that they are fractals. The great power of these techniques is that they link growth to specific geometrical forms. They can be easily generalized to other forms such as those with the characteristics of percolation clusters (see Makse *et al*, 1995; Peterson, 1996). They are consistent with the sorts of scaling found in the physics of critical phenomena, particularly in structures which are far-from-equilibrium (see Feder, 1988; Batty and Xie, 1999). More importantly, the DLA model suggests a technique to define urban structures and to measure urban densities more accurately than existing quantitative models. For instance, populations can be measured more accurately at actual point locations, not over areas or volumes.

In the last 10 years, more advanced models using simulation techniques have been developed. Langlois and Phipps (1995) examined how land uses restructure themselves to form self-organizing but segregated fractal patterns. More recently, the applications of such segregated patterns emerged from explicit migration models have been developed by other scholars (e.g. Vanbergue *et al*, 2000). While these applications mostly focus on processing data, on one factor of the city – such as in "SimCity for Real" created by Clarke *et al* (2008) for simulating population patterns, – the City Analysis Simulation Tool (CAST) developed by Jankovic *et al* (2005) took a step forward to process many factors together including economics, land-use and transport (figure 4.29). What follows is a summary of how CAST processes data.

Like other cellular based models, CAST uses a raster-based grid, which divides the city into cells. The classification of the cell type is based on the main land-use types (22 types). These are not separately mapped; rather they are treated as infrastructure of the cells. Central to the operation of CAST is the fact that in general there are not many top down imposed rules; instead the processes within the cells are free to evolve based on the rules within the cells. The model considers several flows within the city, but the key one for the CAST is the flow of money, the income of cells, gained through employment and from taxation (Jankovic *et al*, 2005). This flow of money (fitness) connects the cells and drives the changes:

- Decrease/increase in fitness of cells
- Intensification/decline of current activity within cells
- Change of use of cell type (land-use)

Jankovic *et al* (2005) claimed that CAST recognizes the city as an open system too and, therefore, some external rules such as planning policies such as sets of limits on height and density of buildings, or even the global actions such as the state of the world economy, can be imported to influence action within the cells.

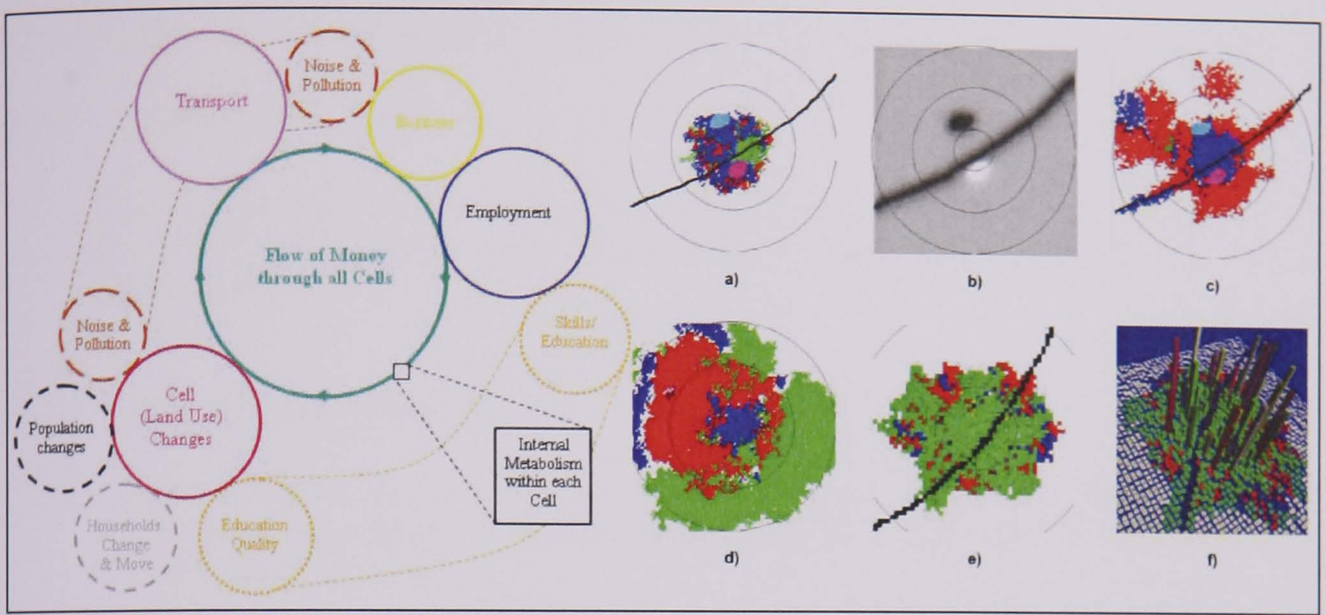

Figure 4.29: Left, the diagram of flows in CAST. Right, examples of CAST output: a) the interface with cell expansion in progress, b) the interface with attractors and repellents, c) road flowing, obtained as an emergent property of the model, d) expansion of the land-use over time, e) two-dimensional land use with major and minor roads, f) a dynamic simulation with GIS data. (Jankovic *et al,* 2005, pp.9-12)

The project was funded by the EU and its detail is not available to the public, and its validity has not been tested more widely by scientists and practitioners outside the lab. However, taking into account the limitation of any simulation models (CA, DLA, SimCity, CAST…), it can be argued that all these models somehow resemble the processes of change or growth in cities, but it can hardly be claimed that they can predict growth or change. This is firstly because the transition rules governing the growth of a city in reality are much more complex than those used in the proposed models, and secondly because of the nature of random behaviour in both CA and the real situation in a city, where given slightly different initial conditions, the outcomes of the process would be hugely different, and therefore, impossible to predict.

In this sense, the main advantage of these models is at most in exploratory scenario making rather than forecasting (Wilson, 2000). Nevertheless, simulation methods can provide a more realistic and accurate vision on how systems behave, and therefore, they are much more suitable for analyzing urban systems than the traditional deterministic methods. Wyatt (1996) stated that:

> 'It should be fairly obvious that such a computationally intensive approach is far more flexible and adaptive than traditional modelling methods' Wyatt (1996, p.650).

4.2.3 Measuring city complexity

> 'Fractal measurement is useful as a method of simulating and testing design production incorporating the levels of complexity that typify urban development' (Cooper, 2000, unpaginated).

Many authors refer to the fractal dimension as a means of measuring the physical complexity of city elements. Fractal measurement methods have been shown to be useful for studying urban forms from global scales (e.g. regional geography) to local scales (architectural design). At large city scales, Batty and Longley (1994) employed fractal measurement to reveal the complex and seemingly irregular physical urban form such as urban boundaries and city edges. At building scales, Jencks (1997), Bovill (1996), and others applied fractal dimension as a means of evaluating of architectural products, as discussed in the first part of this chapter. At the middle ground of city scale, however, Stamps (2002) and Cooper (2003) tested the concept on fractal skylines, Taylor *et al* (2001), Gotou (2002) *et al,* and Hagerhall *et al* (2004) linked fractal dimensions and landscape preferences, and Cooper and Oskrochi (2008) employed fractal dimension as a potential tool for assessing levels of visual variety in street vistas.

Cooper's (2000) work is a key reference in studying of urban morphological complexity. It explores comprehensive fractal measurements of different urban elements at the neighbourhood scale (street level) of the city of Oxford, including street vistas, street elevations, skylines, and building lines. To establish his argument, Cooper (2000) compared the results of fractal measurements to a morphological survey of networks and streets, and to a subjective survey presenting expert perceptions of the sample in terms of permeability, legibility, visual variety, and enclosure. He concluded that the new sciences – fractals and chaos – are useful to urban design in terms of evaluating the complex nature of urban forms as a means of character assessment. More recently, Cooper and Oskrochi (2008) provide an example of how fractal analysis can measure the complexity of street vistas linking the calculation of fractal dimension to the perception of levels of visual variety present in everyday urban streets.

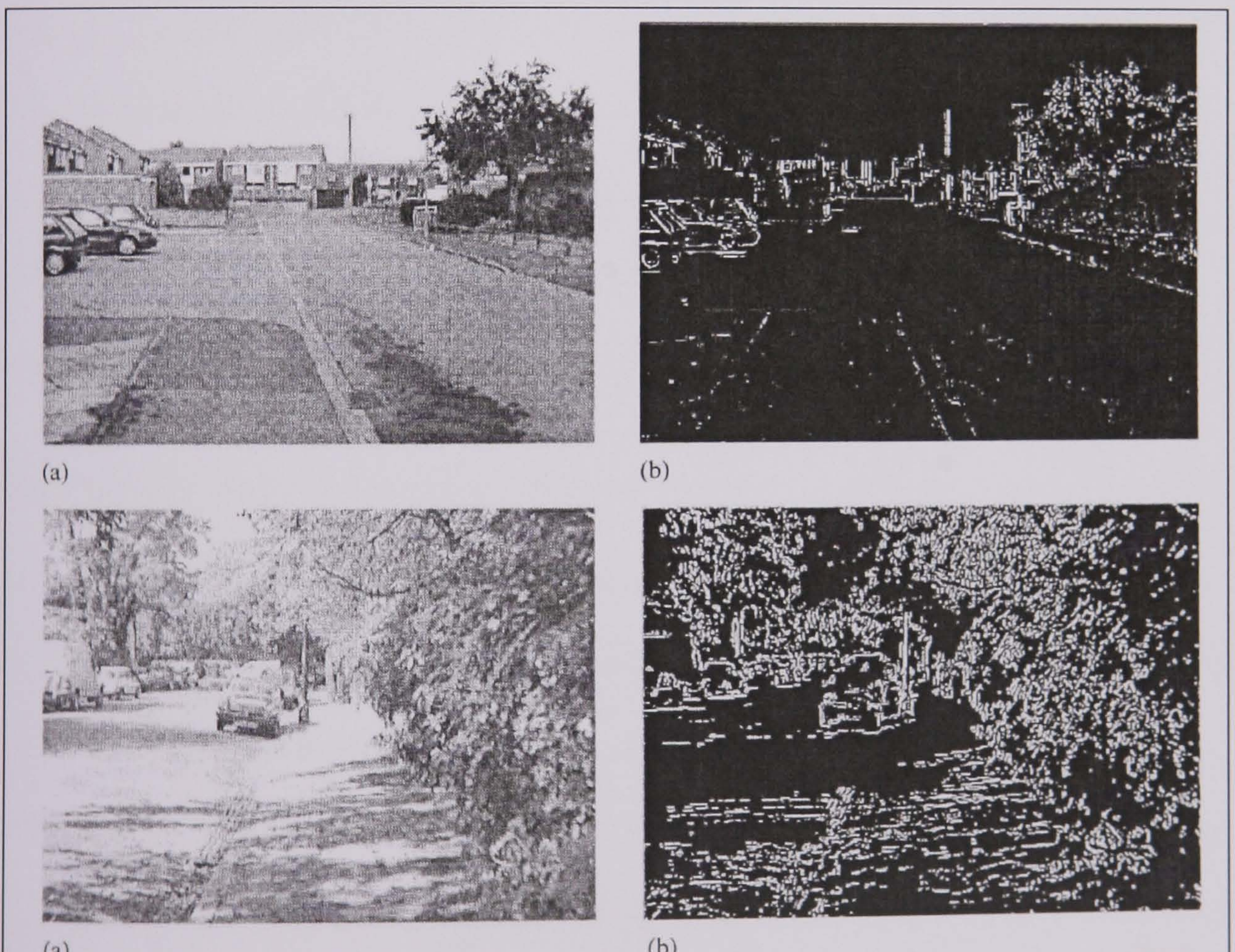

Figure 4.30: Above, a greyscale image and its edge detected pixels of a street in Oxford which has a low fractal dimension (Db) of 1.434 with low visual variety. Below, another street in Oxford which has a high fractal dimension (Db) of 1.825 with high visual variety. (Cooper and Oskrochi, 2008, p.356)

Cooper and Oskrochi (2008) employed the "box counting" technique – introduced earlier in chapter three – for calculating fractal dimensions (Db) of textures extracted from 240 greyscale images of selected streets in the city of Oxford. According to his survey, the resultant Db values for the 240 individual cases range from 1.434 to 1.825 (figure 4.30).

By asking the respondent to score the visual variety of 26 sets of images, Cooper and Oskrochi (2008, p.360) concluded that 'assessing the correlation between average visual variety scores and fractal dimension scores suggests that there is strong association between these two measures'. They also argued that the fractal concept can be a formula for automatically achieving the degree of variety recognized as essential to human wellbeing. Cooper (2000, 2003, 2005) carried out similar examinations for a series of urban elements such as skylines, street elevations, street edges, etc and found that the fractal dimension responds sensitively to the spatial characteristics (e.g. permeability, legibility, visual variety). Accordingly, he succeeded to demonstrate the fractal measurement as a useful technique to quantify the urban design qualitative.

At the city scale, Batty and Longley (1994) also presented a number of ways in which fractal measurement could be applied in studying urban structures, including urban boundaries and edges, fractal distribution of land-use and population, and fractal analysis of city size, growth, and change. In the case of the city boundary, they measured the fractal dimensions of urban boundaries of Cardiff in 1886, 1901, 1922, and 1949. Batty and Longley (1994, p.181) explained that 'these times have been chosen because of the rapid urban growth of the city from a population of 80,000 to 230,000 during this period. This period also marked the development of tramway system... predominant style of late Victorian worker housing ... the pinnacle of industrial prosperity in Cardiff'.

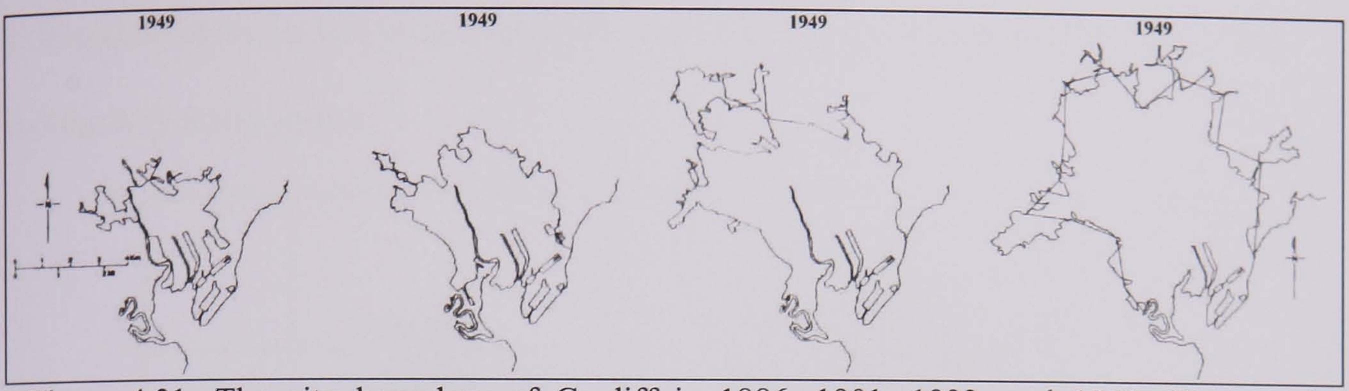

Figure 4.31: The city boundary of Cardiff in 1886, 1901, 1992, and 1949. (Batty and Longley, 1994, pp.175, 181)

Batty and Longley (1994) first created a digitized format of Cardiff's boundary maps at these dates (figure 4.31), followed by calculating fractal dimension through four different methods: the Structured (Ruler) Walk, Equipaced Polygon, Hybrid Walk and finally Cell-Count methods. The results are summarized in table 4.6.

Method / Years	Fractal Dimensions			
	Structured walk	Equipaced Polygon	Hybrid Walk	Cell-Count
1886	1.239	1.236	1.248	1.267
1901	1.184	1.178	1.190	1.200
1922	1.186	1.172	1.190	1.209
1949	1.267	1.293	1.308	1.274

Table 4.6: The results of the fractal calculation of Cardiff city's boundary by four different methods from 1886 to 1949. (Batty and Longley, 1994, pp.189-197)

Based on the results of their fractal survey, Batty and Longley (1994) concluded that: firstly, the city boundary is multi-fractal across a range of scales; secondly, the fractal dimension decreases with the scale of control whenever and wherever the greater control had been instituted over physical development building technology and land development at smaller scales. Finally, they argued that it would be less clear how the fractal dimension changes at larger scales, although increasing mobility and accessibility could imply to decrease it through time.

Batty and Longley (1994) have also carried out another survey to analyse fractally the growth of London from 1820 to 1962 (figure 4.32). They have suggested that the change in fractal dimensions can be used as a sensitive indication of the change in urban form and the way a city grows.

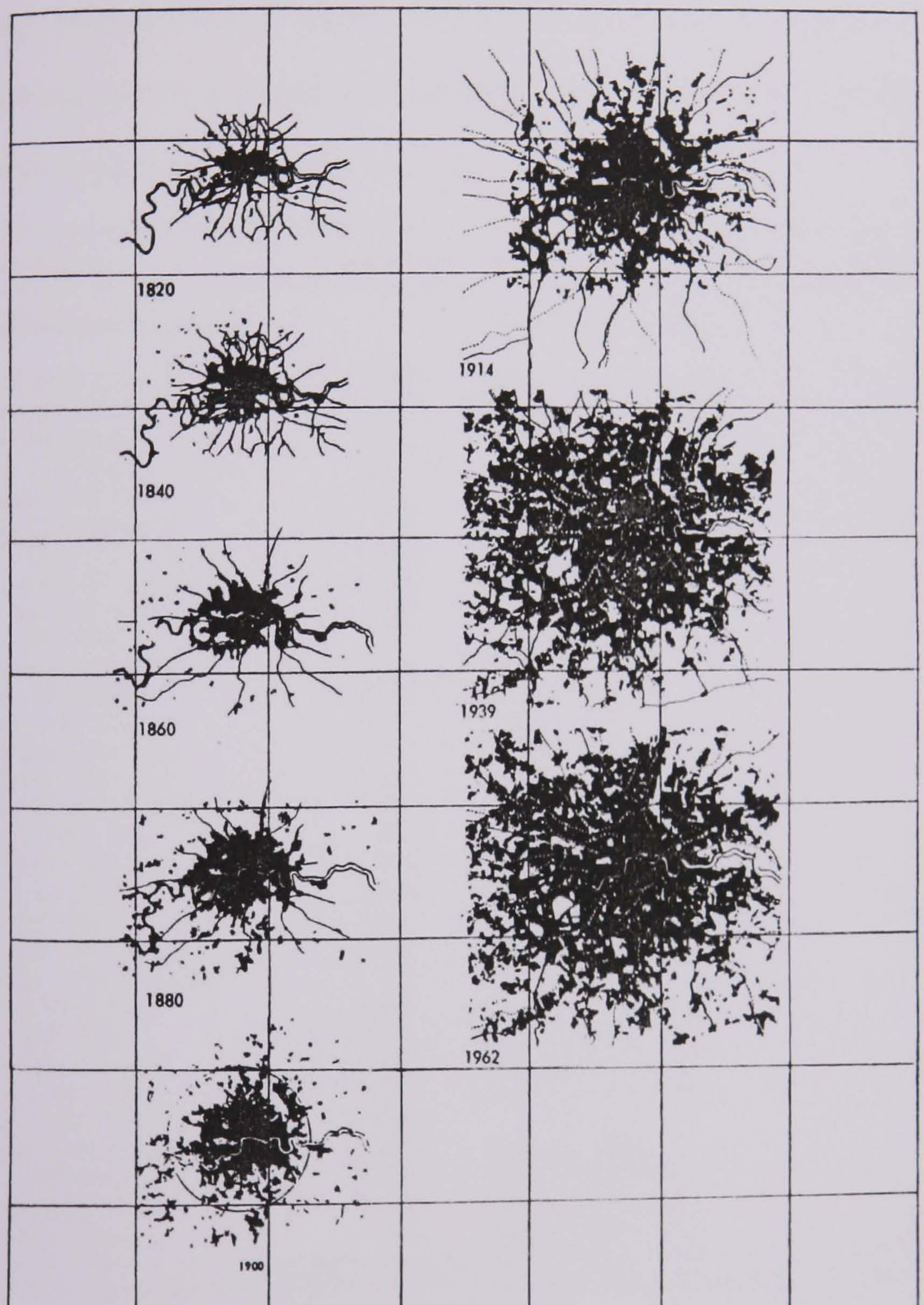

Figure 4.32: The growth of London from 1820 to 1962 and the change in the value of the fractal dimension. (Batty and Longley, 1994, p.239; the Fb values are added to the sides of the figure by the author)

Batty and Longley (1994, p.236) state that 'the increase in values during this time is quite consistent with our analysis of the growth of Cardiff…. as cities grow, they come to fill their space more efficiently and compactly (or at least homogeneously) due to better coordination of development, and increased control over physical form due to better technology'. Their observation, together with the similar work by Frankhauser (1997, 1998) and Smith (1991), provided further evidence for their theory of fractal cities. The result of their work is summarized in table 4.7.

Settlement name	Dimension D	Settlement name	Dimension D
Urban development patterns		*Urban growth patterns*	
Albany 1990 (Chap 7)	1.494	London 1820 (Dox/Ab)	1.322
Beijing 1981 (Fra)	1.93	London 1840 (Dox/Ab)	1.585
Berlin 1980 (Fra)	1.73	London 1860 (Dox/Ab)	1.415
Boston 1981 (Fra)	1.69	London 1880 (Dox/Ab)	1.700
Budapest 1981 (Fra)	1.72	London 1900 (Dox/Ab)	1.737
Buffalo 1990 (Chap 7)	1.729	London 1914 (Dox/Ab)	1.765
Cardiff 1981 (Chap 8)	1.586	London 1939 (Dox/Ab)	1.791
Cleveland 1990 (Chap 7)	1.732	London 1962 (Dox/Ab)	1.774
Columbus 1990 (Chap 7)	1.808		
Essen 1981 (Fra)	1.81	Berlin 1875 (Fra)	1.43
Guatemala 1990 (Sm)	1.702	Berlin 1920 (Fra)	1.54
London 1962 (Dox)	1.774	Berlin 1945 (Fra)	1.69
London 1981 (Fra)	1.72		
Los Angeles 1981 (Fra)	1.93	*Transport networks*	
Melbourne 1981 (Fra)	1.85		
Mexico City 1981 (Fra)	1.76	Suburban Rail	
Moscow 1981 (Fra)	1.60	Lyon I 1987 (T & M)	1.88
New York 1960 (Dox)	1.710	Lyon II 1987 (T & M)	1.655
Paris 1960 (Dox)	1.862	Lyon III 1987 (T & M)	1.64
Paris 1981 (Fra)	1.66	Paris 1989 (B & D)	1.466
Pittsburgh 1981 (Fra)	1.59	Stuttgart 1988 (Fra)	1.58
Pittsburgh 1990 (Chap 7)	1.775		
Potsdam 1945 (Fra)	1.88	*Public bus*	
Rome 1981 (Fra)	1.69	Lyon I 1987 (T & M)	1.45
Seoul 1981 (Chap 9)	1.682	Lyon II 1987 (T & M)	1.00
Stuttgart 1981 (Fra)	1.41	Lyon III 1987 (T & M)	1.09
Sydney 1981 (Fra)	1.82		
Syracuse 1990 (Chap 7)	1.438	*Drainage utilities*	
Taipei 1981 (Fra)	1.39	Lyon I 1987 (T & M)	1.79
Taunton 1981 (Chap 7)	1.636	Lyon II 1987 (T & M)	1.30
Tokyo 1960 (Dox)	1.312	Lyon III 1987 (T & M)	1.21

Table 4.7: The preliminary evidence of the assessed fractal dimension for some cities around the world. (Batty and Longley, p.242)

At regional scales, there are also a number of authors who have examined the applicability of fractal measurement in analyzing urban and geographical patterns such as the city as a surface (Broscoe, 1992; Batty *et al,* 1995); urban traffic network patterns (Jiang *et al,* 2002); river network patterns (Veltri, 2004; Schuller *et al*, 2001); and population density and distribution (Chen and Zhou, 2004; Clarke *et al,* 2008). For instance, Chen and Zhou (2004) employed fractal measurements as a tool to reveal the scaling relationship between rank and size distributions of American cities based on Zipf's model. By making a set of simple models of multi fractal measure, they provided further evidence for symmetry law's of nature in geographical evolution. Chen and Zhou (2004, p.804) concluded that a) the multi-fractal measures reveal some strange symmetry in the regularity of urban hierarchical systems similar to the symmetry laws of nature; b) multi-fractal structure of urban hierarchies results from the contradictory action of the opposites between entropy-maximization and its counteraction in the urban system; and c) the result shows how order assorts with disorder, how the macro-state assorts with micro-state of urban systems, and thus nature harmonizes randomness process with the ordering principle by means of some simple self-organizing rules.

4.3 Chapter Summary

This chapter has examined the meaning of complexity, chaos, and fractals in the context of urban form and function. Fractal theory interprets the physical complexity of urban forms, while chaos theory could explain the functional complexity in the behaviour of urban actors. Recent developments related to the application of complexity theory to urban form and function were reviewed to show how architects, planners, and urban designers could shift their views towards what is claimed to be more realistic in terms of fractal architecture (part one) and fractal cities (part two).

The first part explained the difference between the application of the fractal concept as a design tool and as a critical tool. The notion of fractal architecture was discussed through different examples employing fractal geometry as a design tool. It has also been argued that some buildings may only exhibit a sort of self-similarity which might be misinterpreted as if they have a fractal quality. Euclidian geometry seems to be an inevitable part of their design processes, and in the most cases, they are arguably just a sophisticated design style rather than embodying principles of fractal geometry. Fractal quality is the product of gradual adaptation to environmental factors, and cannot be achieved all at once. The first part of this chapter suggested a list of criteria by which fractal and non-fractal architecture could be better distinguished. This list is not claimed to be comprehensive; however, it assists architects to approach the concept as a design quality rather than a design style.

The second part of the chapter focused on the applications of complexity theory and fractals at the city scale to show how they contribute to conceptualise, simulate, and measure of urban complexity. Complexity theory forges a more conclusive link between physical form of cities and the various socio-economic processes that are central to their functioning. It teaches us that incremental bottom up behaviours of individual citizens and developers as urban actors at architectural scales play the main role in shaping complex urban patterns at micro city scales, and in generating emergent properties at macro city scales (see emergent self-organising properties of complex systems; Chapter Three, sections 3.2.2.7 and 3.2.2.8).

Predictability and certainty as the traditional hallmarks of the top down urban planning have been criticised widely by the complexity theorists. In complex systems thinking, there is always the possibility that such systems can evolve to emergent forms and patterns. Complex systems theory suggests that cities evolve through the incremental actions of local agents, which generate highly ordered global patterns, and a small change in the behaviour of local actors may result in unexpected properties and patterns (see also Chapter Three, sections 3.2.2.5 and 3.2.2.6). Furthermore, on a global basis, cities as chaotic systems are unpredictable because of the cumulative effects of various kinds of feedback. Cell-based urban simulation models provide detail analysis of the micro behaviour of local actors (cells) acting individually and interactively with a series of feedback effects.

Therefore, cities are predictable only on a local basis; and the patterns that "emerge" from local interaction and random decisions of individuals are not possible to be determined by a comprehensive master plan. However, the bottom up nature of urban change has been ignored by many modernist planners in the 20th centuries. Their proposed master plans have mainly followed a deterministic top down routine with predictable and certain outcomes simplifying urban problems for purposes of control (see also Chapter Five, sections 5.1.3 and 5.1.4, where it examines the failure of top down master planning in particular case studies of Iranian cities including Tehran).

Experts in complex systems planning have proposed new planning models to replace top down urban planning with a bottom up approach (Chapter Four, section 4.2.1.2.2), however, their attempts have been only at theoretical and laboratorial levels. There are few practical tools available to provide this shift and to promote these models to a practical level. Fractal simulation models together with fractal assessment tools including the one developed during the course of this research contribute to the above need. This chapter reviewed some of the recent work of the researchers who employed fractal dimension as a means of measuring the physical complexity of urban forms from global to local city scales. The fractal assessment methods are shown to be useful in analysing the levels of complexity that an urban element poses. The following chapters aim to examine and analyse the research case study through the principles of complex systems thinking and fractal geometry in order to promote the current fractal analysis method to a more practical level.

CHAPTER FIVE

THE IMPLICATIONS OF THE CONVENTIONAL MASTER PLANS OF TEHRAN FOR URBAN GROWTH AND FORM: CASE STUDY SELECTION AND INTERPRETATION

Introduction

The previous chapter discussed theoretical aspects of the inefficiency of the conventional planning methods to adapt themselves to real city behaviour and change. This chapter follows two main purposes: The first is to identify the inadequacy of the conventional top down urban planning in controlling the patterns of urban growth in the particular case of Tehran. The second is to select some sample cases that are appropriate for testing the capabilities of the fractal analysis tool, developed through the course of this research. Selection of a case study at the city and district scales will respond to the first purpose, and selection of appropriate samples within the case study at the neighbourhood scale will respond to the second one.

This chapter, therefore, consists of two main parts. The first explores the changes occurring in the last two centuries in Tehran city's structure and elaborates the failures of conventional planning approaches to predict or control these changes. The second part, however, will focus on selected samples at a neighbourhood scale. The factors that have led to those selections are discussed. Both parts together will provide the means for the fractal examination and analysis of the selected cases in subsequent chapters.

5.1 Part One: The Impacts of the Conventional Master Plans (comprehensive plans) in Controlling Urban Change in Tehran and Other Iranian Cities

The previous chapter highlighted some weaknesses of master plans as implemented under the utopian and deterministic views of modernist planners and system theorist planners during the last century. Proponents of complex systems planning claim that reducing the flexibility of urban planning and policies by imposing limits through a top down process, in order to maintain an urban fabric in equilibrium, could not cope with the reality of the change in urban systems which are, in fact, far-from-equilibrium.

The failures of conventional master plans in Iranian cities in general, and the case study of Tehran in particular, confirm that claim. Urban growth and change in Tehran are briefly reviewed to understand why conventional planning approaches mainly failed to achieve their goals. Tehran has experienced enormous morphological changes – incorporating both planned and organic developments – making it a good case study for analysing the consequences of top down master planning and measuring quantitatively the degree of urban morphological change (see also section 5.2.1).

5.1.1 The history of urban growth, large scale planning, and interventions in Tehran

Tehran's main planning efforts relate to four periods whereby large-scale infrastructure projects set the framework for the city's growth and development: a) before 1786 when the village of Tehran developed into a small town and was walled for the first time, b) between 1786 and 1925 when it became the Iranian capital city and the walls were expanded, c) from 1925 up to 1965, when the walls were removed and the city network expanded based on grid patterns, and finally d) after 1965, when a series of modernist planning attempts built a new urban infrastructure.

5.1.1.1 <u>The initial period (pre-1786):</u>

In the 16th century, Tehran was only a small village, outside the ancient city of Ray, which lay at the intersection of two major trade highways: the east-west historic Silk Road along the southern edge of Alborz Mountains and the north-south route that connected the Caspian Sea to the Persian Gulf. Ray had been inhabited for thousands of years and was the capital of the Seljuk dynasty in the 11th century; however, it declined at the end of the medieval period, when Tehran began to grow (Lockhart, 1960).

Tehran was known for its comfortable climate, and therefore it drew the attention of some Safavid kings who passed through while travelling. King Tahmasb ordered its fortification in 1553. It is, in fact, the first large-scale planning with the construction of a bazaar and city walls, which were square and had gates on four sides, in accordance with the pattern of ancient Persian cities (Barthold, 1984; Saeednia, 1991).

In the 17th century there were only five thousand houses and, as illustrated in figure 5.1, these formed four distinctive neighbourhoods. As with other Iranian urban structures, all neighbourhoods met up with the main axis of the bazaar. The branches of the main bazaar became transformed into a *bazaarcheh* (small cluster of shops and stands) as the main street of each neighbourhood (Faghih, 1977).

Figure 5.1: The first map of Tehran in 1841 (Berezin Map). (Habibi and Hourcade, 2005, p.66)

5.1.1.2 <u>The second period (1785-1920):</u>

The selection of Tehran as the capital city of Iran in 1785 by the first king of Qajar was the starting point for other developments (Saeednia 1991; Habibi 1995). From a population of 15,000 at the end of the 18th century, Tehran grew tenfold by the 1860s. After nearly a century of slow and organic growth, a new plan was drawn up in 1871, which was, in fact, the second large-scale planning transformation for the city. Faghih (1977) states that the Naseri plan[1] was based on the concept of an ideal Renaissance city: a perfect octagon similar to the 18th century walled cities, with twelve gates. In other words, Tehran was enclosed in a neat and orderly fashion (figure 5.2). At this time, the population was 150,000 and the city included ten neighbourhoods (Saeednia, 1991).

[1] The name refers to Naser-e-Din Shah, one of the kings of the Qajar dynasty, who ordered an octagonal shape for Tehran's plan.

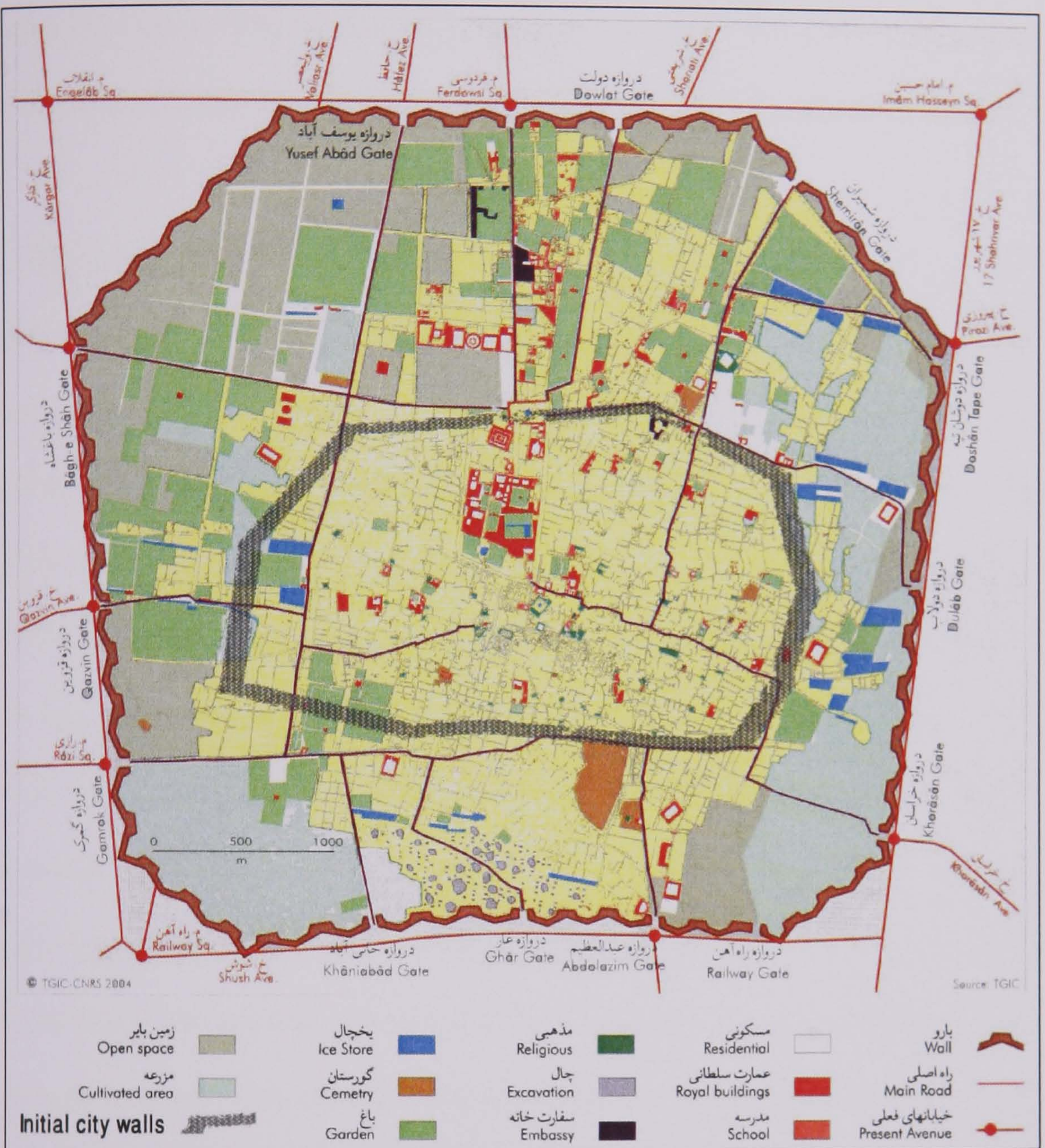

Figure 5.2: Map of Tehran drawn by Abd-ol-Ghafar Khan in 1891. The new octagonal wall, as compared to the footprint of the initial city wall, indicates the first planned expansion of the city in a neat and orderly fashion. (Sahab, 1991, p.291; reproduced in Habibi and Hourcade, 2005, p.68, the initial city walls marked by the author)

Selection as the capital city, and the new transformations which included a new central square, new streets, a bank, an Institute of Technology (Dar-al-Fonoon), a hospital, a telegraph house, hotels and European style shops, were – according to the British observer Curzon (1892, p.300) – a 'twofold renaissance' for Tehran. However, on the contrary, the organically grown neighbourhood patterns remained unplanned, which was interpreted by another English traveller, William Jackson (1903), as: "east and west [of the city] combine imperfectly in its mixed civilization" (quoted in Faghih, 1977, p.47).

5.1.1.3 The third period (1925-1965):

After the decline of Qajar and with the dominance of Pahlavi in 1925, fundamental changes were imposed to the structure of the city by Reza Pahlavi (the first king of the Pahlavi dynasty). Modernisation was the main aim of the new regime resulting from the constitutional revolution of 1906. A modern municipality was established in 1910, transforming the old system of urban governance, and cutting the links to the past. 'In 1930, a new urban strategy, similar to Haussmann's ideas for Paris, was approved by Municipality of Tehran' (Municipality of Tehran, 2004, p.69). The city walls were destroyed and new boulevards were built on the ruins of the walls and moats, as part of a transport network of 218 km of new roads. During the 1930s there were also widespread street-widening schemes that tore apart the historic urban fabric, making areas accessible to motor vehicles. Western industrial cities became the prototypes for a changing Tehran (Municipality of Tehran, 2004; see also Hourcade and Adle, 1997).

The city of Tehran thus went through its third large-scale transformation by 1937. It was 'radically re-planned and re-built' (Lockhart, 1939, p.11). At this time, retailers were encouraged to move to the new streets and abandon the old ones around the bazaar. As a result, a considerable part of Tehran's residential sector (belonging to the new middle classes) also moved from the older to the new sections of the city (Faghih, 1977). During this period, the introduction of the international style led to the creation of a street-oriented urban architecture, and the idea of residential blocks was introduced to the city. The walled royal compound in the city centre was fragmented and replaced by new governmental buildings (Habibi, 1996).

Apart from the main changes in the city centre, the city walls were destroyed between 1932 and 1937, and the city was completely transformed with the imposition of the new transportation network. The new street network was imposed on the winding streets of old neighbourhoods with the aim of unifying the space of the city. It was a major step in laying the foundation for further modernization and future expansion of the city. Figure 5.3 illustrates the urban growth from 1891 to 1953.

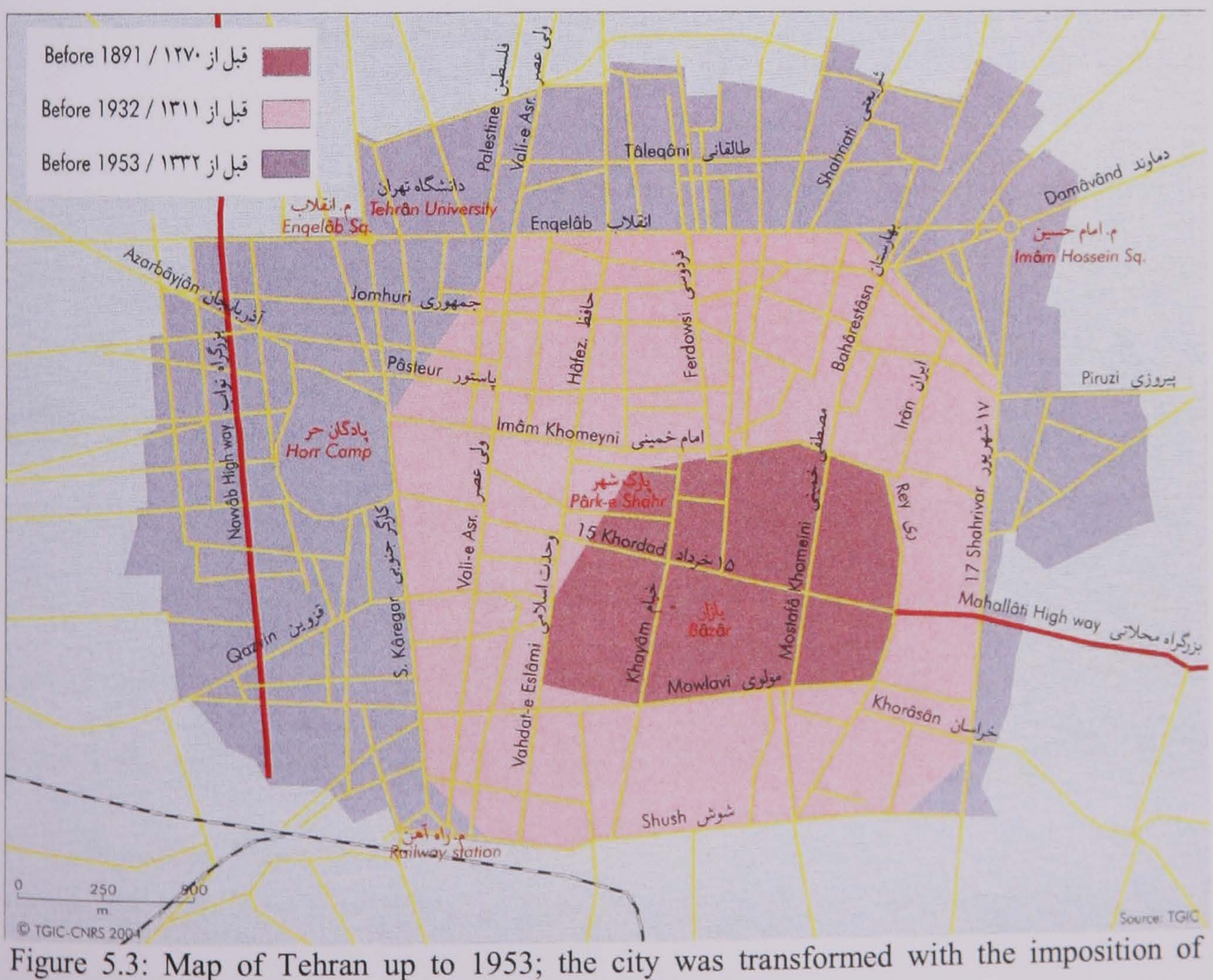

Figure 5.3: Map of Tehran up to 1953; the city was transformed with the imposition of transportation network. (Municipality of Tehran, 2004, p.59)

The changes in the concept of planning, both in the overall image of the city and the architecture of the individual buildings, had drastic implications for neighbourhood pattern and structure. There are two different views of these changes. While many have criticised the destruction of historical buildings including 12 beautiful city gates (Saeednia 1991; Habibi 1996; Abrahamian, 1982), some have emphasized its positive aspects (Kariman, 1976; Faghih 1977). For instance, referring to the urban changes up to the 1960s, Faghih (1977) pointed out that city life as a whole became much more active and gave the new urban pattern a broader expression. She listed the urban design characteristics found in some residential areas as pedestrian continuity, exposed architectural details, and elements at street level, rows of building with orderly layout, clearly defined open spaces and mixed land use.

The immediate result was a dramatic population growth; from 310,000 inhabitants in 1932 to 750,000 in 1941, then to 2.8 million in 1966, and to 4.5 million 1976. In just 35 years, the population increased six fold (Habibi, 1989, p.18). More important than demographic change was the impact of socio-economic forces which sometimes resulted in paradoxical spatial developments. Embracing the market economy divided the city along the lines of income and wealth, tradition and modernity. Rich and poor, who used to live side-by-side in the old city, were now separated. Modernizers welcomed living in new neighbourhoods and frequented new streets (the city north), while traditionalists continued to live and work in older parts of the city (the city south).

5.1.1.4 The fourth period (after 1965):

A modern type of planning emerged in Tehran in the 1960s, preparing plans to regulate and manage future change. The city had grown in size and complexity to such an extent that its spatial management needed additional tools, which resulted in increasing complexity of the administration of municipal organization, and the preparation of the first comprehensive plan for the city following some of modernist principles of the master plans – 'planning through land-use regulation' (Madanipour, 2003, p.144).

The 1966 Municipality Act provided, for the first time, a legal framework for the formation of the Urban Planning High Council (UPHC) and for the establishment of land-use planning in the form of comprehensive plans (figure 5.4a). In 1968, the UPHC approved the Tehran Comprehensive Plan which was produced by a consortium of Aziz Farmanfarmaian Associates of Iran and Victor Gruen Associates of the United States, under the direction of Fereydun Ghaffari, an Iranian city planner (Ardalan, 1986).

The proposals were mostly advocating physical change (Farmanfarmaian and Gruen, 1968), such as:

- Attempting, in a modernist sprit, to impose a new order onto this complex metropolis, incorporating the following features.
- Growing westward in linear polycentric form.
- Reducing the density and congestion of the city centre.
- Assigning a new city boundary to be formed by 10 large urban districts with about 500 thousand inhabitants each.

- Separating districts by green belts.
- Subdividing district (*mantaghe*) into a number of areas (*nahieh*) and neighbourhoods (*mahaleh*).
- Allocating a high school, a commercial centre, and other necessary facilities for each area with a population of about 15 to 30,000.
- Allocating a primary school and a local commercial centre for a neighbourhood with its 5000 inhabitants.
- Linking these districts by a transportation network – this included a hierarchy of streets, motorways, rapid transit routes, and bus routes.

Almost all of these features can be traced to the fashionable urban planning ideas of the time, which seemed to be largely influenced by mechanical approaches – especially the zoning idea of modernism, in which everything was determined and fixed. Unsurprisingly, it resembled Gruen's (1965) "metropolis for tomorrow," which had suggested a central city surrounded by 10 additional cities, each with its own centre. It had also the elements of the Howard's idea of the "garden cities" in which a central city was surrounded by a cluster of satellite settlements separated by green belts (Howard, 1902). The use of neighbourhood units of limited population – focused on the neighbourhood centre and primary school – was widely used in new towns based on the Howard's suggestions, but was particularly developed in the 1920s in the United States (Mumford, 1954).

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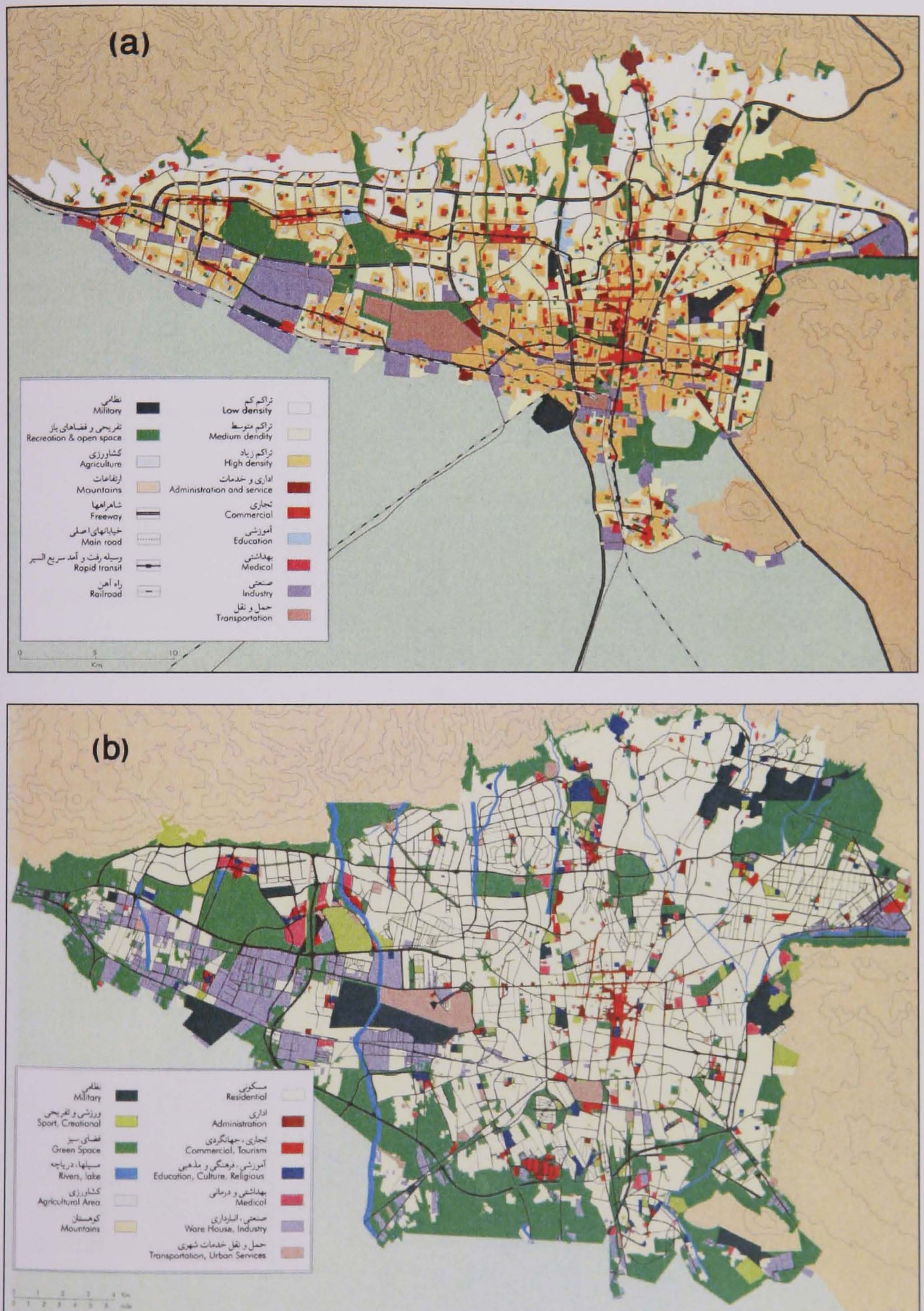


Figure 5.4: Tehran's Master Plans (Comprehensive Plans) shown together to aid comparison; a) Farmanfarmaian plan - the first master plan in 1968; b) ATEC Plan - the revised master plan in 1992. (Habibi and Hourcade, 2005, pp.74-75)

As discussed in Chapter Four, structuralism as part of the systematic view of urban planning was developed in the second half of the 20th century. It was based on the belief that urban design and planning aimed to create and maintain a core structure for a city instead of outlining every element and providing a maximum flexibility for other developments linked to the main structure. In Tehran, based on this structural approach to the city system, two major planning exercises were carried out initially in 1970s and more comprehensively in 1990s (Madanipour, 1998, 2003).

In the 1970s, the British consultant Llewelyn Davies proposed a plan which included the partial development of a new high-rise residential centre, Shahrak-e Gharb, and the planning of a new administrative and business centre for the city, Shahestan, as a systematic way to control the change and growth (figure 5.5). However, the latter was not developed before 1979, the Islamic revolution (Madanipour, 1998; Mashhoudi, 2007).

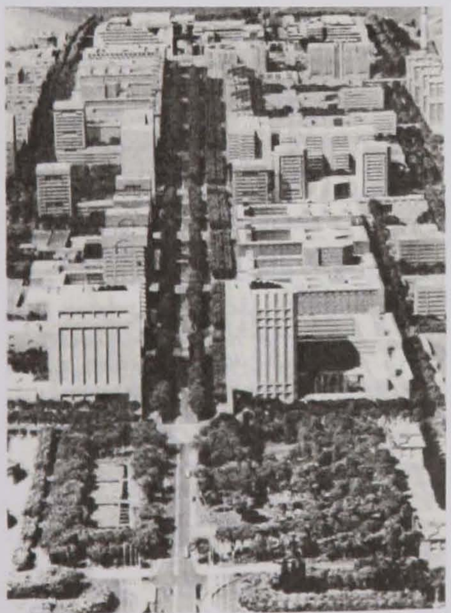


Figure 5.5: Left; The model of Shahestan-e Pahlavi; an administrative zone with ministry' offices on both sides. Right; Shahrak-e Gharb; High rise residential complexes in the north-west of Tehran (Hourcade and Adle, 1997, p.240)

Other examples of structural planning in Tehran are the Ekbatan Complex (1975-1995), and the Navab Project (1993-2003). The Ekbatan complex was built in 3 phases over 20 years (figure 5.6, left). It is the largest residential complex in the west of Tehran and planned on a self-contained town. In the poorer area in the south, a major redevelopment project, Navab, cut a motorway through the dense and decayed urban fabric; and imposed mega-structural building blocks on each side (figure 5.6, right).

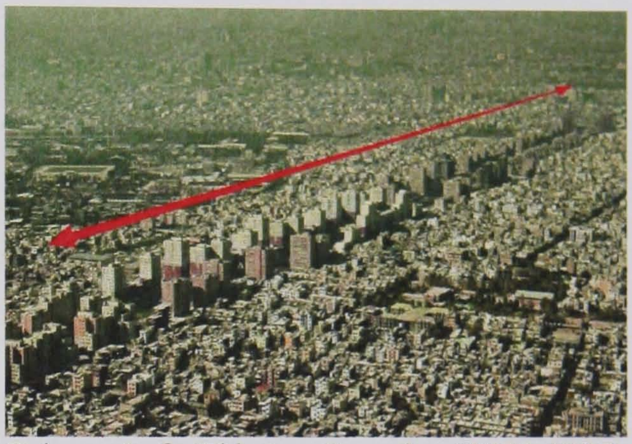


Figure 5.6: Two examples of structural planning in Tehran. Left; Ekbatan Complex (1975-1995). Right; Navab Project (1993-2003). (Municipality of Tehran, 2004)

In the1990s, the first comprehensive plan's 25-year period ended. A firm of Iranian consultants (A-Tech) proposed a plan for Tehran for the period of 1986-1996. However, this plan was revised by the municipality in 1993 before being implemented. The final approved plan also focused on growth management, linear spatial development, and a policy-based strategy rather than the former land-use plan (Municipality of Tehran, 2004). The new plan consisted of the following main features:

- Polycentric development in the city
- Creation of new parks and green spaces
- Development of cultural and community centres
- Increasing residential densities
- Improvement of urban spaces by implementing regeneration projects
- Assignment of 22 districts within the 5 sub-regions, each with its own service centre
- Development of the transportation network to ease movement in the city

5.1.2 Tehran's current condition

Population growth continued during the recent decades, mostly due to the large-scale immigration. Tehran's population including its suburban residential districts increased 15 times – from 210,000 in 1931 to 10.3 million in 1996, of which 6.8 million live within the city limits of Tehran and the rest within Tehran metropolitan region (PRCTN [Planning and Research Centre of Tehran], 2006). In the same period, however, the total population of Iran increased only 6 times – from 9.8 million to 60 million.

Tehran, which had only a 2% share of the country's whole population in 1931, now incorporates more than 15%. This is the result of migration due to the capital's unique attractions – more than 40% of the nation's economic activities take place there. It is anticipated that the population of Tehran with its suburban districts will reach around 14 millions in the year 2011 (ACAUP [Atec Consulting Architects and Urban Planners], 2002). The density of different residential districts is very varied. However, the average population density is nearly 105 persons per hectare. The following bar chart clearly shows the population explosion in the second half of the 20th century (SCI [Statistical Centre of Iran], 2001).

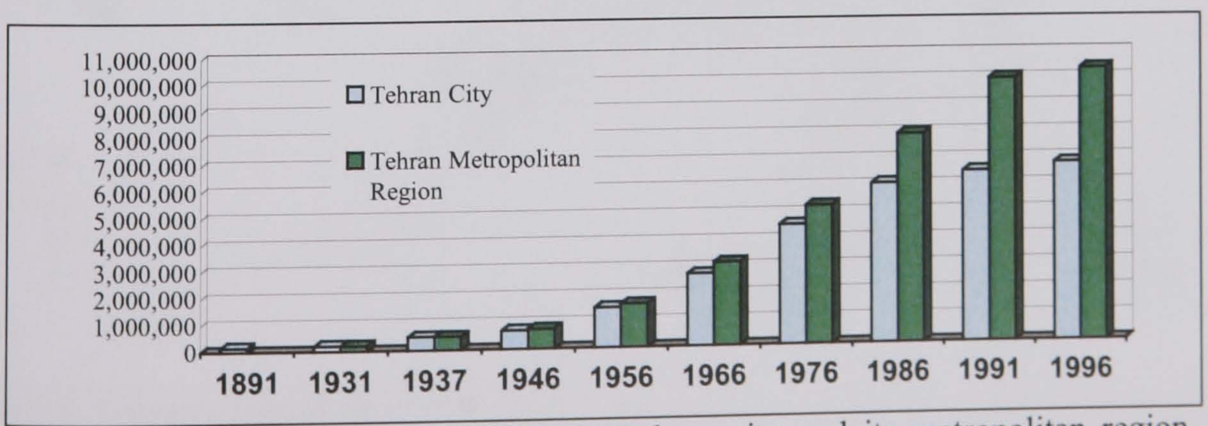


Figure 5.7: The demographic growth in Tehran city and its metropolitan region. (SCI, 2001, unpaginated)

The consequence of this population explosion in the 20th century was the huge expansion of the city boundary. The city administrative boundary was expanded twice, first outward and then westward, to encompass 22 district municipalities in 720 km^2. Tehran's area increased from 46 km^2 to 250 km^2 just in 42 years (1934-1976); and for just 22 years thereafter (1976-1998), irrespective of the suburban areas, the area of the city increased to 720 km^2 (Zanjani, 1999). Many housing developments were built inside and outside Tehran's boundaries. The expansion of the city required new roads. Several motorways and arterial roads were added to the previous street network of the city and were extended to the peripheral – new suburban – areas (figure 5.8).

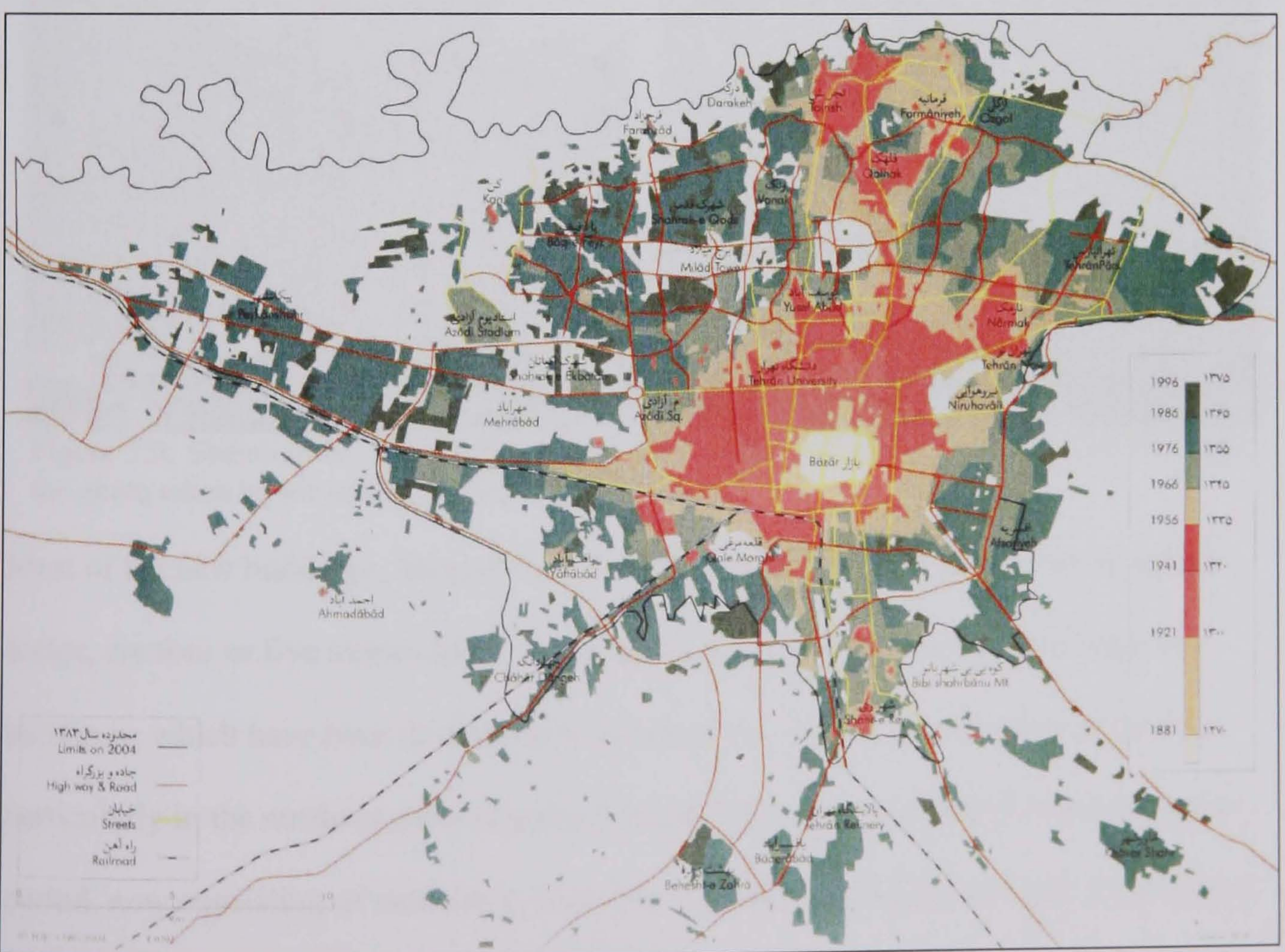


Figure 5.8: Tehran's growth up to 2004 and its new network system; the rapid growth of Tehran has transformed the city to a metropolis dominated by a network of motorways. (Habibi and Hourcade, 2005, p.60)

The first planning priority for these new parts of the city has been ease of car access. Therefore, the regular grid street layout is the dominant planning concern of almost all these areas. Nearly all of the new streets are wide enough to be responsive to future population growth. New housing developments are mostly located on the gap between the earlier city boundaries and the old villages around the city. Many of the new developments are established by specific governmental offices to accommodate their employees and therefore have a population with a common occupation. Shops and urban facilities have gradually developed in clusters around roundabouts or main street corners.

Figure 5.9: Shemiran in 1957 (left), and in 2005 (right). (Left, Kariman, 1976, p.53; Right. the photo taken by the author, February 2005)

Most of the new buildings, irrespective of whether developed by the private or public sector, are four or five stories high. There are also considerable amounts of high-rise buildings, which have been developed in recent years. As a result, the face of the city, particularly in the northern parts (figures 5.9 and 5.5, right), was transformed in a short period, now consisting of medium to high-rise buildings connected through wide streets and motorways similar to Le Corbusier's Radiant City (see also appendix D). However, in the most cases sufficient open and green spaces have not been provided.

5.1.3 The overall comments on the former master plans of Tehran

The key urban planning stages in the 20th century (1930s, 1960s, and 1990s) mark the periods of relative economic and political strength, in which urban development flourished, and the government felt able to manage the growth. Since Tehran became the Iranian capital (1785), several large-scale plans have been produced. Although they succeeded, to some extent, in steering the course of events and developed a more sophisticated approach to planning, these plans all have much that has remained unimplemented.

Yet the intensity of speculative development – especially since the Second World War – and the speed of events seem to have left the city authorities and citizens alike feeling trapped in turmoil, lagging behind the events, and unable to manage change (Madanipour, 2003; Mashhoudi, 2007). The intensified social and physical segregation destroyed suburban gardens and green spaces in a way that left the city managers feeling powerless. A deputy mayor of the city in 1962 commented that:

> '... the buildings and settlements [in Tehran] have been developed by whoever has wanted in whatever way and wherever they have wanted' (quoted in Nafisi, 1964, p.426).

None of the laws and urban policies that have been imposed by Tehran's master plans helped to control the growth and changes. Land use patterns were determined in a static way and were unable to adapt and absorb the new needs and changes. Some other weaknesses of conventional master plans of Tehran can be outlined as:

- Even though since 1990, there have been some democratic elements in Tehran's master plans, they have shown strong modernist tendencies, with centralising governance where urban interventions remaining their favourite device similar to previous planning generations (see also Hourcade, 2000).

- There are many high-rise residential complexes and offices, which lack urban facilities, such as proper road accesses and defined parking spaces.
- The most consistent problems relating to the city has been traffic and air pollution (add a figure showing the traffic). Tehran's air is currently among the most polluted in the world (Bahrainy, 1989; Ghiasodin, 1999; PRCTN, 2006).
- There are no defined open spaces for social activities and human attraction, except for a few local parks or playgrounds for children.
- The metropolitan city of Tehran grew during the last two centuries in a way that provided diverse, fragmented, disjoined, and contradictory urban patterns.

Many researchers have argued that citizens are in favour of having a sense of community and neighbourhood identity (Tavalai *et al*, 1992; Homayouni, 1995; Bahrainy, 1989). However, the new residential developments in Tehran have no distinctive character. Tehran has experienced the destruction of its past visual order and harmony by new and modern developments during the last century (Hourcade and Adle, 1997). This caused the city to lose its pre-modern characteristics without offering a new integral identity for the whole city (figure 5.10).

In the city of Tehran, there is a huge contrast between the ideals of the proposed master plans and the realities on the ground. An important question to ask is why 'the gap between planned ideal and reality is almost always great' (Larkham, 2006, p.123). Is it the result of bad management (the inability of Tehran's authorities to implement the comprehensive plans), the lack of expertise of the planners who proposed the plans, or the consequence of the top down deterministic planning approaches that failed to cope with ongoing urban changes on the ground? In the next section, the records in relation to the master plans proposed for other Iranian cities will be explored to find a reliable answer to the above question.

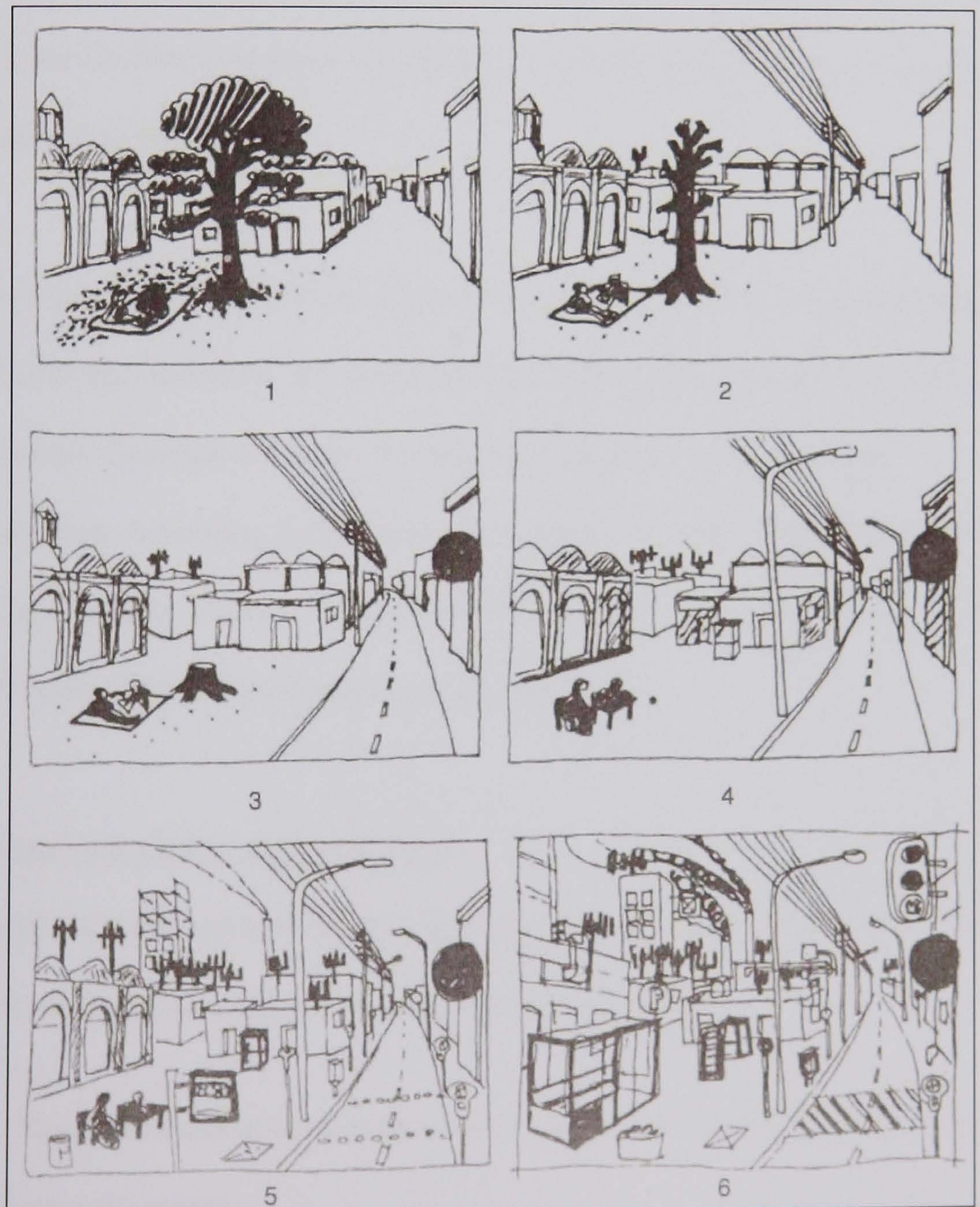


Figure 5.10: A caricature illustrating changes to street vistas in Tehran during the 20th century. (Hourcade and Adle, 1997, p.251)

5.1.4 The failures of the top down master planning in managing change in other Iranian cities

In 1994, Zista Consultants conducted an important study for the highest planning authority in the government – the Budget and Planning Organization. The study aimed to assess the achievements and inadequacies of conventional master planning in Iranian cities in the last 25 years. Eighteen major cities were initially selected and classified in seven categories based on the following criteria: population, population growth, the economic basis of them at city scale, their economic potentials at regional scale, climate, and geographical features.

One sample city was selected from each category (Shiraz, Arak, Yazd, Maragheh, Bandar Abbas, Rasht and Zahedan). All seven had two master plans and the study was based on the comparison between the goals of these plans and the reality after their implementation. According to the survey undertaken by Zista Consultants (1994), what actually happened in reality is far from the earlier plans' goals and predictions of the proposed plans. This survey is briefly reviewed below.

5.1.4.1 <u>Economic studies and predictions</u>:

The general economic pattern shows a lack of success in the plans. As shown in table 5.1, predictions in the three economic activity groups are as follows:

a) The predictions of employment in the agriculture sector differed from 0.1 to 2.2 times the actual.

b) The predictions of employment in the industrial sector varied from 42% less to 63% more than the actual.

c) The predictions of employment in the services sector varied from 50% less to 30% more than the actual.

Sample Cities	Agriculture		Industry		Services	
	Predictions (Ideal)	Actual Census (Reality)	Predictions (Ideal)	Actual Census (Reality)	Predictions (Ideal)	Actual Census (Reality)
Zahedan	3.6%	2.1%	24.5%	42.5%	71.9%	55.4%
Arak	3%	1.47%	52.5%	38%	44.5%	39%
Shiraz	1%	2.2%	37%	23.4%	37%	74.4%
Rasht	20%	2%	45%	27.5%	35%	70.5%
Bandar Abbas	2.5%	1.7%	41%	35.8%	60.4%	58.1%
Yazd	4.5%	3.8%	58%	72.3%	63.5%	55.2%

Table 5.1: Increase rate of employment (percentage). The predictions for the year 1991 were compared with what actually has happened. (Derived from Zista Consultants, 1994)

5.1.4.2 Population:

The results of the study show that the predictions of population growth in the sample cities were 65-143% more than the actual numbers. 70% of the predictions were grossly mistaken, ranging from 30% less to 43% more. Only in 15% of the cases were the predictions reasonably accurate.

5.1.4.3 Prediction in settlement land-use:

Table 5.2 shows a summary of the correspondence of the predictions and the actual figures at which assessed at the end of the plan (per capita). In general, green areas, sports, recreational, and non-profit lands were less than predicted.

Sample Cities	Residential	Roads & Streets	Parks & Sports	Public Services	Commercials & Private Services
Maragheh	92%	135%	95%	58%	78%
Arak	112%	113%	131%	32%	40%
Rasht	96%	84%	6%	50%	30%
Zahedan	70%	121%	23%	39%	135%
Yazd	121%	129%	93%	44%	140%
Shiraz	82%	82%	5%	106%	127%
Bandar Abbas	53%	55%	115%	95%	24%
Average	90%	103%	53%	60%	82%

Table 5.2: The percentages per capita indicating the difference between the proposed plan (ideal) and actual figures (reality). (Derived from Zista Consultants, 1994)

5.1.4.4 Assessment of the directions and zones the city has expanded:

Table 5.3 presents a summary of the result of the survey regarding the growth and developments inside and outside the sample cities' predicted boundaries. In all of them 3 to 26% of expansion was outside the planned areas, while 10-40% of lands in the areas were not built despite of what had been planned.

	Maragheh	Arak	Rasht	Zahedan	Yazd	Shiraz	Bandar Abbas	Average
Percentage constructed outside the zone	20%	8%	15%	15%	20%	26%	3%	15%
Percentage un-constructed inside the zone	30%	40%	19.5%	22%	10%	30%	22%	23%

Table 5.3: The built-up area inside and outside the proposed boundary. (Derived from Zista Consultants, 1994)

5.1.4.5 Assessment of network expansion:

Table 5.4 provides a summary of the conformity between the prediction and actual events in relation to the changes which have occurred in the street network. On average, only 24% of the proposed streets were built within the planning period and the others have not been constructed yet. Meanwhile, 16% to 83% of the built streets were not mentioned in their proposed master plans.

	Percentage of built streets	Percentage of built street without planning	Note
Maragheh	25%	-	-
Arak	26%	32%	-
Rasht	22%	28%	-
Zahedan	21%	83%	-
Yazd	30%	-	-
Shiraz	25%	-	2 of the streets that should have been built in the plan have been omitted.
Bandar Abbas	16%	16%	-
Average	24%	23%	-

Table 5.4: the percentage of the streets constructed based on the proposed plan (Derived from Zista Consultants, 1994)

5.1.4.6 <u>The correspondence of proposed densities with the actual occurred densities</u>:

The changes in built-up, net residential population, and population density were also studied. Built-up densities at the end of plans were an average of 15% lower than what had been predicted. Net residential density at the end of plan was from 17% lower to 42% higher of the predictions. The survey revealed that only in one case the prediction was to some extent came true; however, in others the error ranges from 17% to 60%.

5.1.4.7 <u>The changes in the city structure</u>:

In all cases, the master plans had proposed a modern layout of urban patterns where the zones for land-uses were determined and services had been planned in the centre of local areas at neighbourhoods' level, far from main roads. However, the analysis revealed that, in all cases, the cities did not follow the plan, and the services were dispersed at local area centres or along the major roads based on the scale of the business and the market needs.

5.1.5 The overall comments on the conventional urban planning in Iran:

In short, the studies on the master plans of Tehran and this sample of cities revealed that what actually occurred, in reality, hardly ever corresponded to the original objectives of the plans. Mashhoudi (2007, p.3) concludes that:

> 'It seems that the city itself evades all instructions and planning, and reaches a point of defiance where anything that "should not be", imposes itself on those that "should be". The city apparently uses its own creativity to go anyway except the one planned for it.'

Zista Consultants (1994) reported that the failure of the master plans cannot be blamed on lack or inadequacy of data, nor can planners be blamed for their lack of expertise, nor can the authorities be blamed for their inability in implementing the plans. In fact, the cognitive methods of urban planners had no conformity with the complex nature of urban evolution and their efforts to recognise the urban complexities by simplifying and generalising the problems only worsened the crises. Zista Consultants (1994) concluded that the roots of the failures lay in the following reasons:

- Impossibility of accurate prediction of changes, particularly in economic and social issues
- Ignorance of the changes in citizen needs during the planning implementation period and their role in actively participating in making decisions
- Ignorance of the change in physical potentials of the environment
- Rigidity of the plans in determining the land uses, zone` boundaries, and enforcing certain sizes and population limits to the cities

Zebardast (2004) has also noted the impracticability of the conventional planning methods. He believes that land-use restrictions within the city, rigid municipal boundaries, insufficient investments in infrastructure that commensurate with new needs, and the rigidity of the urban planning system in Iran to adapt to fast demographic change, have resulted in the overspill of low income groups into the periphery. Therefore, the formation of informal settlements in Iran has more to do with inflexibility of urban planning regulations than with the weak administration and management. This has also been reflected by the World Bank:

> 'It is the inflexibility of urban planning regulations and the inability to integrate areas on the periphery that renders most of these settlements [urban fringes] informal' (World Bank, 2002, p.15).

The failures of the master plans in Iranian cities in general, and in the case study of Tehran in particular, conform to the outcome of the theoretical debate discussed in the previous chapter, in which the top down and deterministic approaches in conventional planning were criticised. In fact, without shifting our planning methods from utopian and deterministic ones – from the city in equilibrium – to more flexible, democratic, and complex ones – the city in a fragile equilibrium – planning, and management of Tehran and other cities remain less effective.

5.2 Part Two: The Case Study of Shemiran and Sample Selection

In Part One, the history of urban growth in Tehran was briefly reviewed. It was mentioned that Tehran experienced a huge expansion of its suburbs during the 20th century. However, this was in a disjointed manner in all directions, along the roads, integrating the surrounding towns and villages (Madanipour, 2003). Reviewing the history of urban growth in Tehran reveals two different growth patterns. On the one hand, there was a fast and huge expansion of the former city towards its suburbs, and on the other, a gradual organic growth of the villages, which lay around the city in the past but, are now within the city. Therefore, its morphology consists of a number of towns connected to each other in an inappropriate way. As a result, rapid urban growth has produced controversial neighbourhood patterns in different parts of the city including the northern parts (Shemiran). Shemiran with its unique historical, geographical, and social characteristics is a good exemplar of urban pattern diversity.

5.2.1 The factors of case study selection and sample selection

One of the main proposals of this research is that the fractal dimension measurement can be used as a sensitive tool to assess urban morphological change and to identify pattern classification. In order to test this proposal, the following two factors are to be taken into account:

(a) The case study should exhibit elements of both planned and organic growth with a variety of building type and age. One representative from each type is required to make comparison possible.

(b) As the focus of the research is on measuring change over time, the morphological data, maps, and photos of the selected cases should be available from the past to present both at large and small scales.

As discussed earlier, the urban morphology of Tehran experienced both gradual and rapid growth over the last two centuries. Shemiran, a district in the north of Tehran, meets the above two factors due to its structural and morphological diversity and historical data availability. The organic neighbourhood pattern of Tajrish (centre of Shemiran) and the new grid neighbourhood pattern of Velenjak (a new residential development in Shemiran) are appropriate required samples for a comparative pattern analysis. Tajrish is considered as the main sample, because its historical data is available for the change analysis over time (figure 5.11).

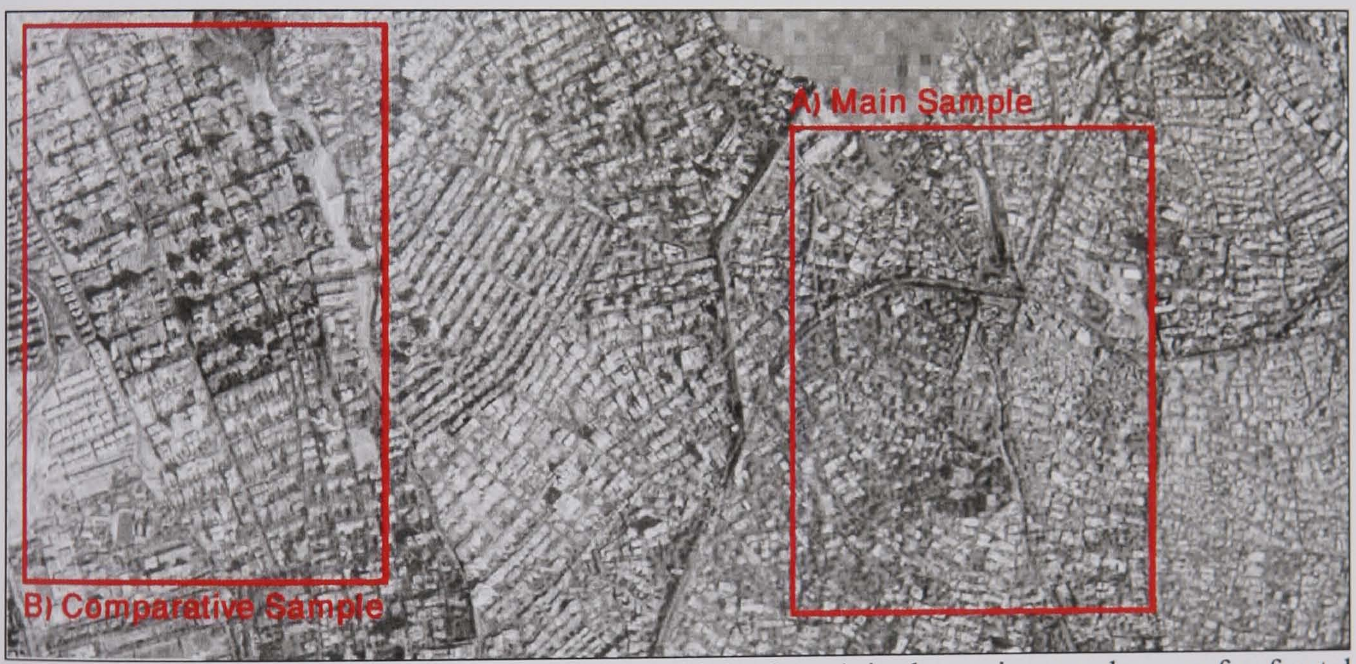


Figure 5.11: Areal photo of Shemiran. Tajrish (right frame) is the main sample case for fractal examination and Velenjak (left frame) will provide the comparative sample.

5.2.2 Historical and geographical interpretation of the urban pattern in Shemiran

There is an influential geographical reason behind the existence of diverse urban patterns in Ray and Shemiran. Shemiran, in the north of Tehran is located on the mountainside of the Alborz chain towards the north of Iran. However, Ray in the south of Tehran is close to the desert, Dasht-e Kavir (figure 5.12). The terminology of these places also discloses such a climatic diversity. “Shemir-” means “cold”, and “-an” means “place”; therefore

"Shemiran" means a "cold place". In contrast, Tehran, in the south, is said to be derived from "Teh-r" and "-an" which means a "warm place" (Hourcade and Adle, 1997, p.14).

Figure 5.12: Tehran's unique geographical location - between the desert and Caspian Sea. (Habibi and Hourcade, 2005)

This is a geographical advantage for Shemiran as it is located on the mountainside – about 800 metres higher than Ray in the south. Due to the different heights of the land, the temperature and rate of rainfall varies remarkably in the north (Shemiran) and the south of the metropolis (Ray) as shown in table 5.5. Therefore, Shemiran with its moderate climate in the summer gradually became a recreational place for residents of Ray and Tehran who had built their private gardens there (Shahri, 1992).

The rate reported for the years between 1996 and 2003	**North of Tehran** (Shemiran\Tajrish)	**City of Tehran** (Centre)	**South of Tehran** (Ray)
Average temperature (C)	**23**	**29**	**30**
Maximum Temperature (C)	**36**	**42**	**43**
Minimum temperature (C)	**-17**	**-6**	**-5**
Annual rainfall (mm)	**104**	**43**	**42**

Table 5.5: The rate of annual temperature and rainfall in Tehran for the years between 1996 and 2003. (IRIMO, 2004)

Such a big differentiation in the geographical and climatic features within Tehran has had an obvious impact on the way in which the city and its suburbs have evolved over time. These influential factors made a clear distinction between the plot layout in the north and in the south of the city (figures 5.13 and 5.14, right). The old urban patterns in the south (city of Tehran and Ray) followed an inward oriented layout of buildings with courtyards (figure 5.13), similar to other Iranian traditional housing located in a hot and dry climate (Hourcade and Adle, 1997). Conversely, old housing patterns in Shemiran, in the north, adopted the Iranian traditional garden layout (figure 5.14, right). An Iranian garden traditionally is divided in four parts by two crossed water paths with a building (*Kooshk*) at their intersection. It was, in fact, an outward layout where the *Kooshk* faced outwards (figure 5.14, right) surrounded with rows of fruit trees, planted in a regular manner (Shahri, 1992).

However, from the first master plan of Tehran (1965) to the present, a new policy (60% land occupation) has imposed a new building layout (figure 5.14, left), which has followed neither the traditional logic nor the climatic and geographical diversity in Tehran. Based on this policy, only 60% of a plot can be occupied by building and the rest must be left free for a front garden. Hourcade and Adle (1997, pp.252-254) argue that 'this policy seemed to be in the favour of modern grid pattern of urban growth rather than traditional socio-cultural Iranian values'. A few gardens have remained from the past as illustrated in figure 5.16: however, the majority have been divided into smaller plots to construct modern buildings according to the policy of permitted land occupation.

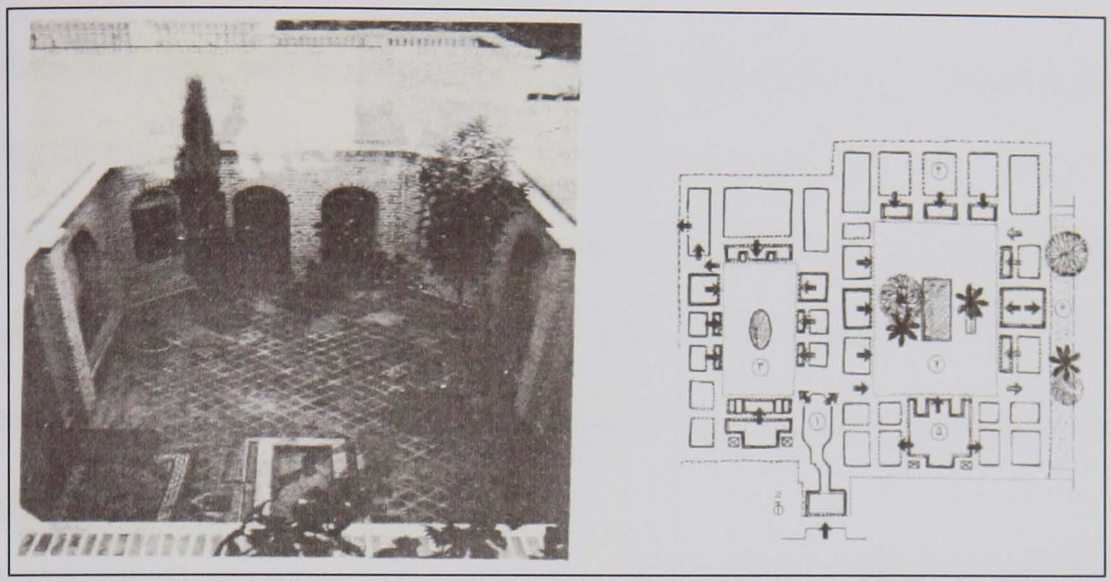


Figure 5.13: A traditional inward plot layout in the south of Tehran, which responds to hot and dry climate in the south of Tehran. (Hourcade and Adle, 1997, p.253)

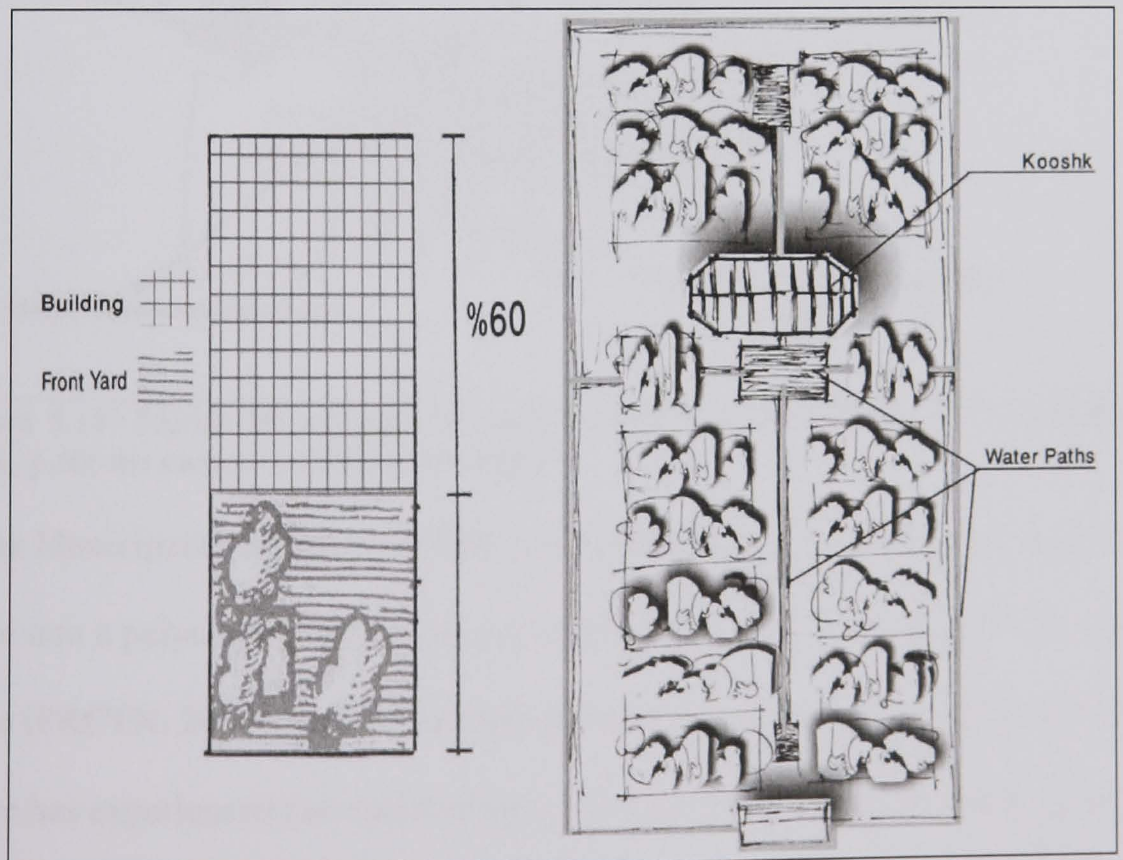


Figure 5.14: Left, the new plot layout has been in force since the first master plan of Tehran – 1968. Right, the typical layout of Persian gardens responds to the climate in Shemiran. (Left, Hourcade and Adle, 1997, p.254; Right, the sketch drawn by the author, April 2008).

5.2.3 Fractal interpretation of the organic urban pattern of Tajrish (the centre of Shemiran)

In Shemiran, the parts, which have developed organically, are mainly around its centre, named "Pol-e Tajrish". Tajrish has the largest traditional shopping mall (bazaar) in the north of Tehran. The origin of the bazaar and the early residential neighbourhoods in Tajrish are linked to the construction of the Shrine – Imamzadeh Saleh – in 11th century (Aboutorabi, 2005, p.66; Sotoudeh, p.200). Figure 5.15 illustrates the Bazaar and its surrounding neighbourhoods.

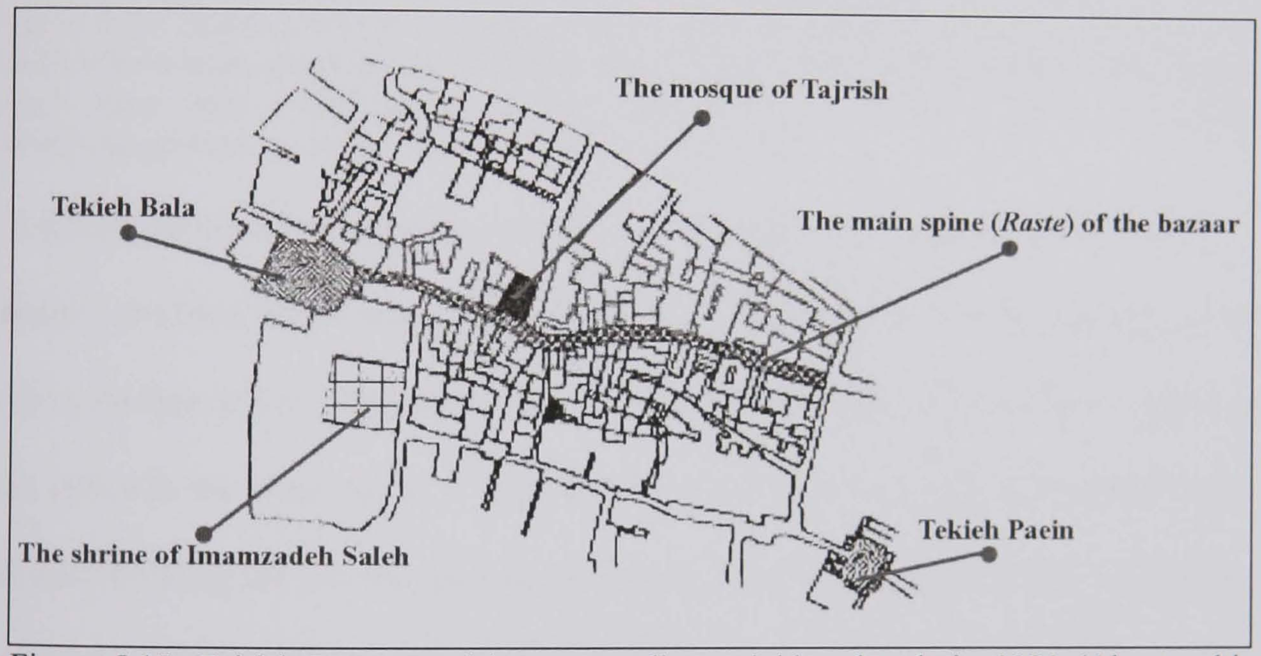


Figure 5.15: Tajrish Bazaar and its surrounding neighbourhoods in 1981 (Aboutorabi, 2005, p.60; the names marked by the author)

Since the Municipality of Tehran aimed to transform the city from a mono-centric structure into a polycentric one and also to encourage hierarchical distribution of urban facilities (PRCTN, 2006), Tajrish has been designated as the main centre in the north and therefore has experienced fast morphological change during recent decades. Only a few old buildings and gardens have remained from the past; however, its existing organic street patterns can be seen as obvious evidence of its long history of organic growth (figure 5.16).

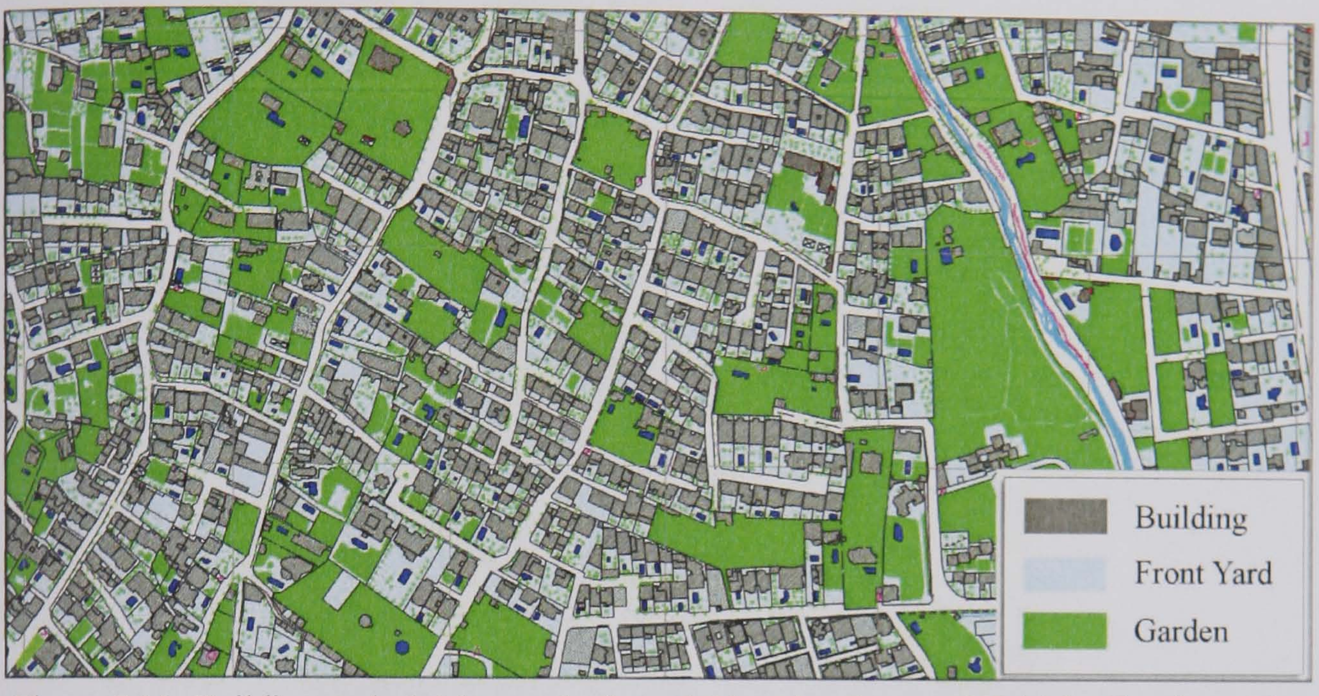


Figure 5.16: Building and plot layout in the neighbourhood area of Tajrish, Shemiran. The gardens have been gradually divided into smaller plots in which the position of buildings and yards have been significantly changed (Municipality of Tehran, 2003, unpaginated; remaining gardens are coloured in dark green by the author).

At a glance, there seems to be no regularity in the neighbourhood pattern of Tajrish; however, on closer observation, some similarity in the building orientation begins to be evident. As figure 5.17 illustrates, a semi U-shaped unit, repeated at different scales and sizes, exists in the urban fabric of Tajrish. This similar unit could be considered as a cell generator creating the site morphological pattern, like the generators of fractal shapes explained in Chapter Three. This self-similar semi U-shape pattern reveals the existence of an underlying geometrical order dominating in the neighbourhoods of Tajrish (figure 5.18).

The preliminary evidence of organic growth with fractal characteristics in Tajrish provides the main sample required for the empirical section of this research. The next section explains how fractal measurement can be useful to interpret and test the diversity of urban patterns in different districts of Tehran, which also assists selection of appropriate case studies for further exploration at the empirical stage.

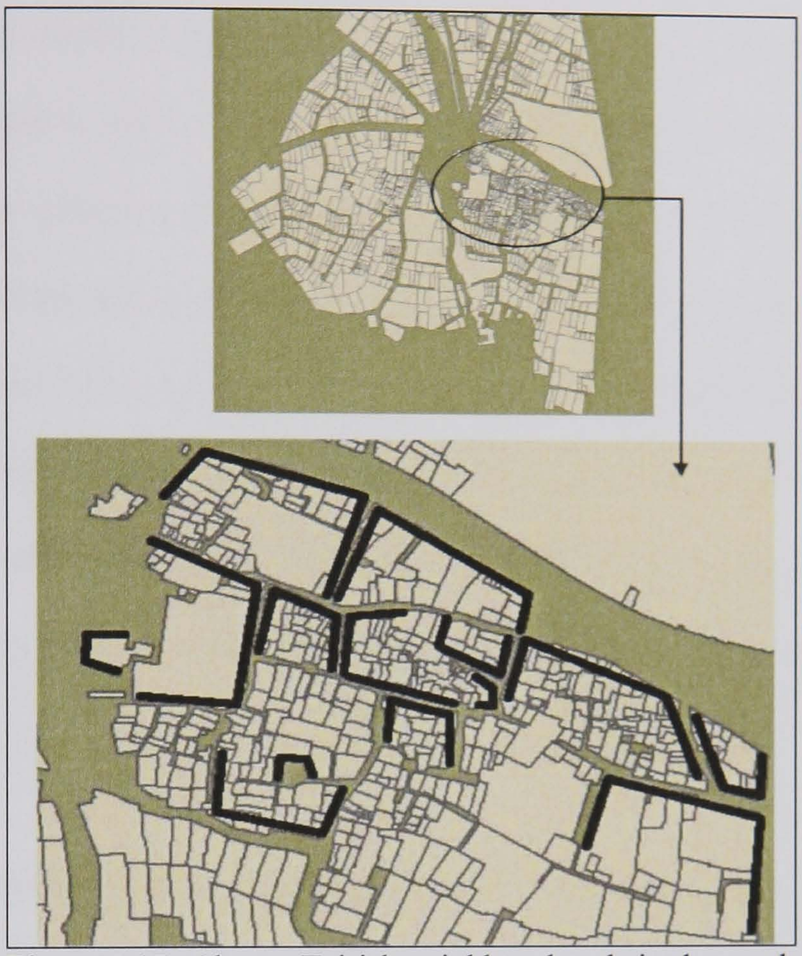


Figure 5.17: Above; Tajrish neighbourhoods in the north of Tehran. Below; self-similar semi U-shape pattern originated from organic urban growth exists at different scale and size of the selected neighbourhood in Tajrish. (Haghani, 2004, p.5)

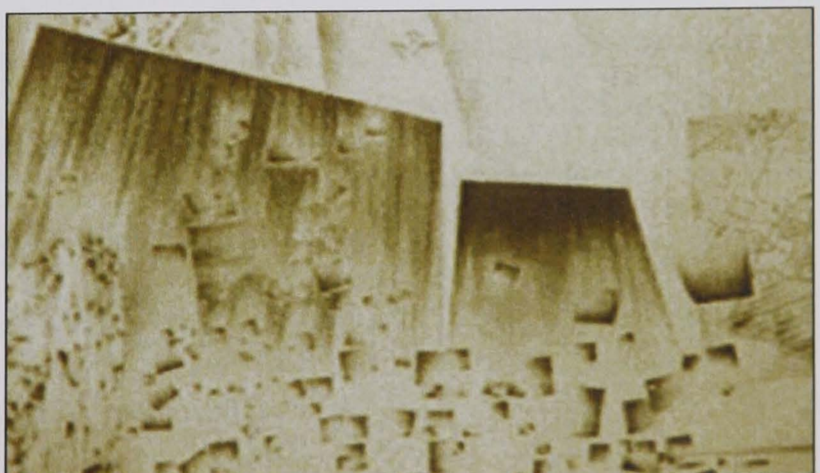


Figure 5.18: A graphic presentation of the distribution of semi U-shaped fractal pattern existing in urban fabric of Tajrish. (Haghani, 2004, p.5)

5.2.4 The case study and sample selection by measuring fractal dimension

Not only a morphological and historical review, but also measuring the fractal dimension of an urban fabric, reveals which districts consist of diverse urban patterns and best meets factor (a) discussed earlier in section 5.2.1. Chapter Three explained that the box counting method can be used for measuring fractal dimension, and can be referred to as an indication of the existence of self-similar shapes (homogenous patterns) or the existence of self-affine shapes (heterogeneous patterns) in a fractal object. As shown in figure 3.25 (Chapter Three, section 3.3.5.1), the logarithmic graphs produced by the box counting method indicate how fractal dimensions assessed for the Koch curve are constant while for the coastline of Britain are varied from large to small scales (figure 3.24, and table 3.2). This indicates that the coastline of Britain consists of heterogeneous fractal patterns.

In a similar way, the fluctuation of calculated fractal dimensions indicates the degree of heterogeneity of urban patterns in an urban fabric. Having produced such logarithmic graphs for the 22 districts of Tehran, the places with maximum and minimum pattern diversity can be identified (refer to appendix C for the graphs of all 22 districts). Each logarithmic graph in figure 5.19 plots the number of occupied pixels, as representative of built up areas, on a graph of which different city scale levels (the horizontal axis) is illustrated. The comparison of the graphs reveals that the developed patterns in district no.1 (Shemiran) and district no.3 are more heterogeneous than the urban patterns in other districts (figure 5.19). Conversely, the stability of the assessed fractal dimensions represented by some of the graphs (e.g. district no.11) is an indication of homogeneity (self-similar urban patterns). Therefore, districts no.1 and no.3 are better candidates for being selected as the research case study and better satisfy factor (a). However, between these two districts, data, photo and maps, are more readily available for Shemiran (District no.1), and therefore, it meets factor (b) too.

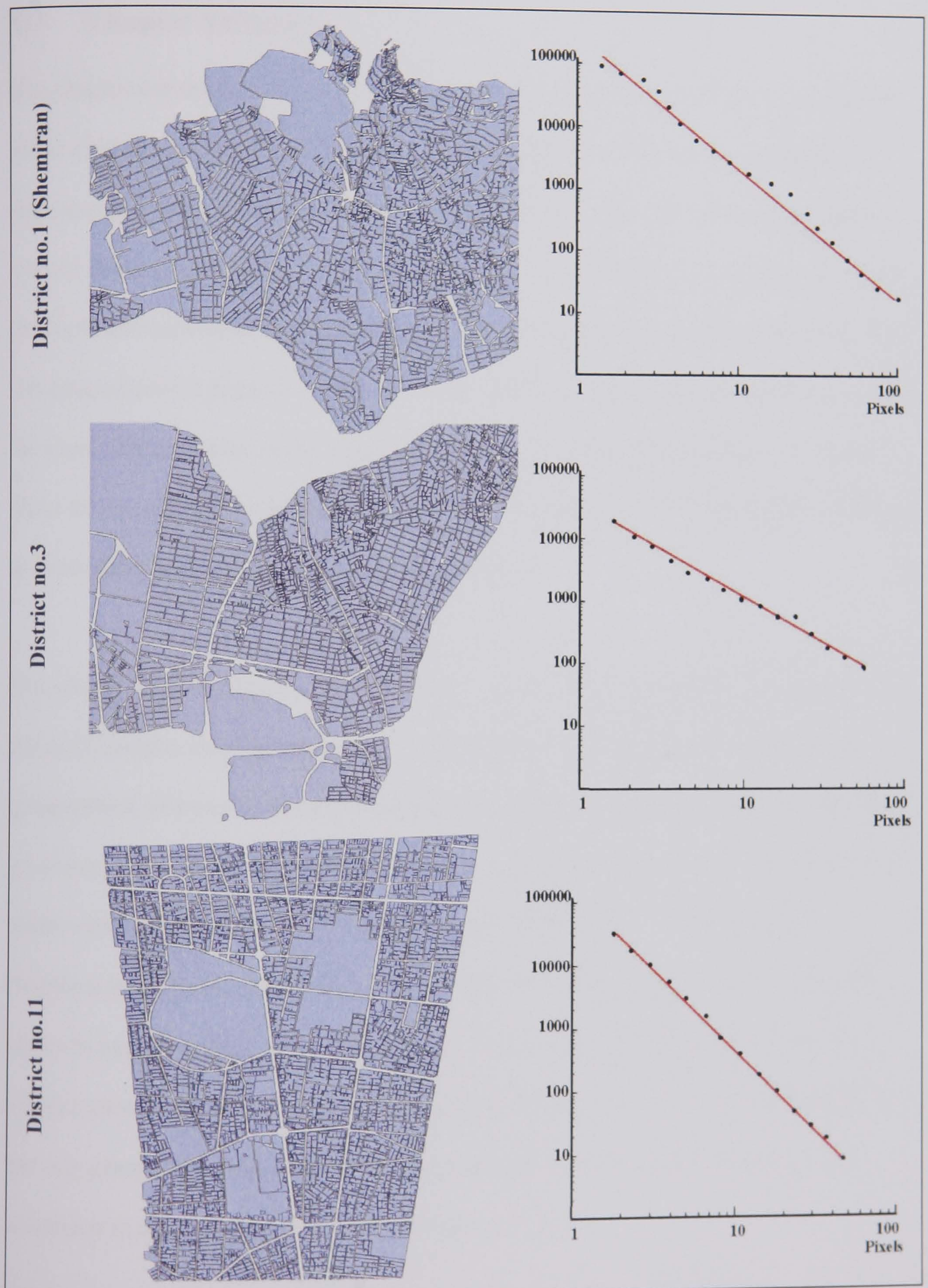


Figure 5.19: Three districts of Tehran with the lowest (above) and highest (middle and below) degrees of pattern diversity according to their respective logarithmic graph. (The graphs are produced by employing the fractal analysis software, Benoit 1.3)

5.3 Chapter Summary:

The chapter achieved its main goal by selecting appropriate case studies at city/district scales (Tehran, Shemiran) and at local neighbourhood scales (Tajrish, Velenjak). As discussed in Part One, recent surveys of Tehran showed that the earlier plans failed to control urban growth and change. It was discussed that the failures have less to do with the weak administration and management than the employed planning methods. In fact, the comprehensive plans of Tehran followed utopian deterministic approaches that were far from what occurred on the ground. In other words, the high expectations of these plans do not conform to the unpredictable and complex nature of actual urban evolution – as discussed theoretically in chapters Three and Four.

One of the main objectives of this research was to measure the degree of change in physical complexity of urban patterns at a neighbourhood scale. Both historical and geographical features of Shemiran suggest that the existing urban patterns are the result of diverse, fragmented, disjoined, and contradictory growth patterns. The initial fractal measurement also reveals the existence of such diversity. Two sample cases at neighbourhood scales of Shemiran were selected to be examined in more detail at the research empirical stage – one with organic and the other with planned origins. The organic growth pattern of Tajrish, the old centre of Shemiran, and the main sample, and the new planned development of Velenjak seemed to be appropriate candidate to be examined in more detail at the research empirical stage.

CHAPTER SIX

FRACTAL MAPPING:
PILOT STUDY AND FRACTAL ASSESSMENT OF THE SELECTED CASE STUDIES

Introduction

Chapter Six narrows down the research by formulating a specific target (see figure 1.3 in Chapter One). Therefore, the chapter will specify an urban morphological feature as its target to be examined. It will attempt to devise a fractal analysis tool to measure more accurately the degree of physical and spatial complexity that the selected case studies exhibit. To achieve this goal, the chapter is comprised of three main parts: a) the research refinement, b) the pilot study, and c) the case study examination.

In the first part, the main outcomes of the previous chapters will be reviewed to formulate the research target and to refine the research method for the empirical stage. The advantages and limitations of the suggested method will also be identified. In the third part, the steps of data processing, image processing, and the preparation the fractal analysis tool will be discussed. In the third part, the fractal dimensions of the selected case studies will be measured in order to produce a fractal map. This map would then be a base for comparing and analysing the morphological changes taking place over both place and time.

6.1 Part One: The Research Target and the Refinement of Method

One of the issues discussed in Chapter Three was that small changes occurring at a local level in a city could become significant changes at a global level (the butterfly effect). Thus, developing appropriate techniques to observe and measure small-scale changes will help to find better ways to analyse the sequence of changes that shape urban patterns at larger scales. At the end of Chapter Four, it was concluded that the views of city complexity in the area of planning and design should focus on bottom up approaches and therefore "architectural and neighbourhood scales" should be the major concern for decision makers. In that chapter, the literature was reviewed to identify the current approaches to urban complexity addressing directly the use of fractal analysis in measuring the complexity of urban elements at architectural and local urban scales.

However, there is little research on the potential of fractal dimension in measuring urban morphological "change" over time. Therefore, this research seeks to cover this less researched area, and to devise a fractal analysis technique addressing the above issues and measuring morphological change at neighbourhood scales. The objectives, therefore, can be elaborated as follows:

I) assessing the fractal dimension of different urban patterns within the case study and comparing the results with the degree of homogeneity or heterogeneity that they display. This will provide a fractal map leading to the fractal classification of urban patterns.

II) Selecting an area within the case study where historical records and data are available and then calculating its spatial fractal dimensions in order to observe and analyse the change in urban shapes and patterns caused by individuals, planning policies, or design proposals.

The latter objective addresses the concerns of complexity theorists related to the changes imposed by large-scale planning and urban design proposals (also known as urban interventions). Chapter Two discussed that Euclidian geometry is the tool in the hand of an architect, urban designer or a planner while planning and drawing proposals, and the imposition of this geometry – particularly on an old urban context – will inevitably create mistakes. It was also suggested that urban interventions are to be treated with extreme caution (Chapter 4), as they may reduce the level of complexity existing in urban system. Therefore, from a morphological point of view, there is a need to develop techniques to measure the degree of changes enforced by an urban intervention in order to evaluate which proposal or urban alternative is better adapted to its existing context. However, no research, so far, has developed such practical techniques; hence, the main goal of the present research is to devise a practical tool that responds to this need.

This chapter develops a fractal analysis tool to assess urban morphological change at a neighbourhood level. In Chapter Five, the case studies in the north of Tehran were selected for a detailed fractal examination. It was explained why these cases could be appropriate to the research aims. The next section will discuss which morphological features of the selected case studies best fulfil the above task and why aerial photos are used as the main source of data.

6.1.1 The source of data for measuring urban morphological evolution

A list of those morphological elements and their properties which can lend themselves to fractal measurement was suggested by Cooper (2000). Fractal dimension measurement can be either applied to each of the elements listed in Table 6.1 or a combination of them can be arranged to be analysed from a fractal point of view. For measuring changes, the important factor is that not only the contemporary data, but also data from the past must be available. For instance, it is possible to measure the degree of change in the fractal dimension of a street façade only if the historic images of the buildings' elevations of that street are available.

<table>
<tr><th colspan="2">Scale</th><th>Element type</th><th>Variable properties</th></tr>
<tr><td></td><td rowspan="7">Neighbourhood Scale</td><td>Street</td><td>Level of connectivity/integration, position in hierarchy, level of predictability/regularity, orientation, skylines irregularity.
Pattern: street pattern*.</td></tr>
<tr><td></td><td>Plot</td><td>Size: width, length, shape, proportion, orientation.
Pattern: ownership patterns and legal basis, level of connection to the street, plot pattern*.</td></tr>
<tr><td></td><td>Building</td><td>Size: width, depth, height, proportion, shape.
Texture of elevation: materials, color, ratio of walls to openings.
Other criteria: level of access, adaptability.</td></tr>
<tr><td rowspan="5">City Scale</td><td>Block</td><td>Size: width, length, shape, orientation, area*, perimeter*.
Pattern: block pattern.</td></tr>
<tr><td>Natural* Element</td><td>Topography (degree and variety of slope), sea and river edges, green spaces (parks, woodlands, and vegetation)</td></tr>
<tr><td>Land use</td><td>Scale of use: extent, intensify and degree of variety.
Pattern: Pattern of land use distribution.</td></tr>
<tr><td>Landmark*</td><td>Type, size, level of visibility, level of accessibility, distribution pattern.</td></tr>
<tr><td></td><td>Boundary*</td><td>City/district boundaries and edges.</td></tr>
</table>

Table 6.1: Measurable morphological elements at city scale and local neighbourhood scale. (Cooper, 2000, p.223; the elements and properties asterisked were added by the author)

As the objective of this research is to measure fractal dimensions of urban morphological patterns at a local urban scale (see Chapter One, section 1.2.1), it has led the research:

a) To focus on the local neighbourhood scale rather than large city scale elements with one exception. The exception is that the survey will require measuring both small-scale and large-scale urban patterns as part of necessary data for formulating a kind of fractal fingerprint for urban neighbourhoods in the next chapter (see section 7.2.1).

b) To use remote sensing city images taken through aerial cartography as the main source of the empirical survey. Aerial photos, in fact, consist of mixture of blocks, plots, and street patterns, which makes linkages with the research objectives. Greenery as part of the urban physical landscape that forms urban patterns was not excluded from the images at the empirical stage. This is also due to the outcome of chapter 5 where the role of greenery conservation as part of Shemiran's physical identity was emphasised.

Using aerial photos as a data source has three advantages: accessibility and reliability of data source, quality of data in the remote sensing survey, and availability of the records. Firstly, the aerial photos have been taken originally by the National Cartographic Centre of Iran (NCCI) and the copies are accessible from the Tehran Geographic Information Centre (TGIC). The advantage of working with this kind of data is that the research can be tested, experimented, and extended by other scholars or practitioners. Secondly, the quality of aerial photos is better than similar images taken by satellite and can pick up the elements as small as 50 centimetres. It would assist testing which resolution better suits the employed method. Finally, the other advantage of using aerial photos as compared to satellite photos is that their history is available. The aerial photos of Tehran – taken and recorded every 10 years since 1956 (see Appendix E) – provide the essential data required for measuring change over time.

6.1.2 Fractal mapping

The main goal of this chapter is to produce the fractal map of the selected case studies – as they are today – based on the fractal dimensions of their urban patterns. Since the research target is to devise a fractal analysis technique to assess changes occurring in urban patterns, the fractal map provides a benchmark by which changes over time to the urban patterns can be measured. The quantitative data that is obtained by assessing fractal dimensions of the patterns at different periods will be converted to pictorial data to identify the potential of the suggested fractal assessment technique in illustrating the evolution of urban patterns.

It is worth emphasising that this research aims to develop only a fractal analysis tool – not an evaluative tool – to assist decision makers to measure more accurately the degree of physical changes. This will assist urban specialists to assess quantitatively the physical impact that an urban intervention or even a new urban policy imposes on an existing urban fabric (see Chapter Seven, sections 7.3.2.1 and 7.3.2.2). As each individual case has its own unique properties and characteristics, it would be the responsibility of decision makers to judge, evaluate and approve any changes caused by the urban development proposals.

6.1.3 An introduction to the employed method and data processing steps

The research suggests a method by which fractal dimensions can be mapped. For this purpose, it has employed fractal analysis software (Benoit 1.3) linked with ArcGIS software (ArcMap 9.2). Benoit 1.3 is used for its ability to calculate fractal dimensions of urban patterns at different scales (producing quantitative data). Then, ArcMap 9.2 is employed to convert the quantitative data into pictorial data (producing a fractal map).

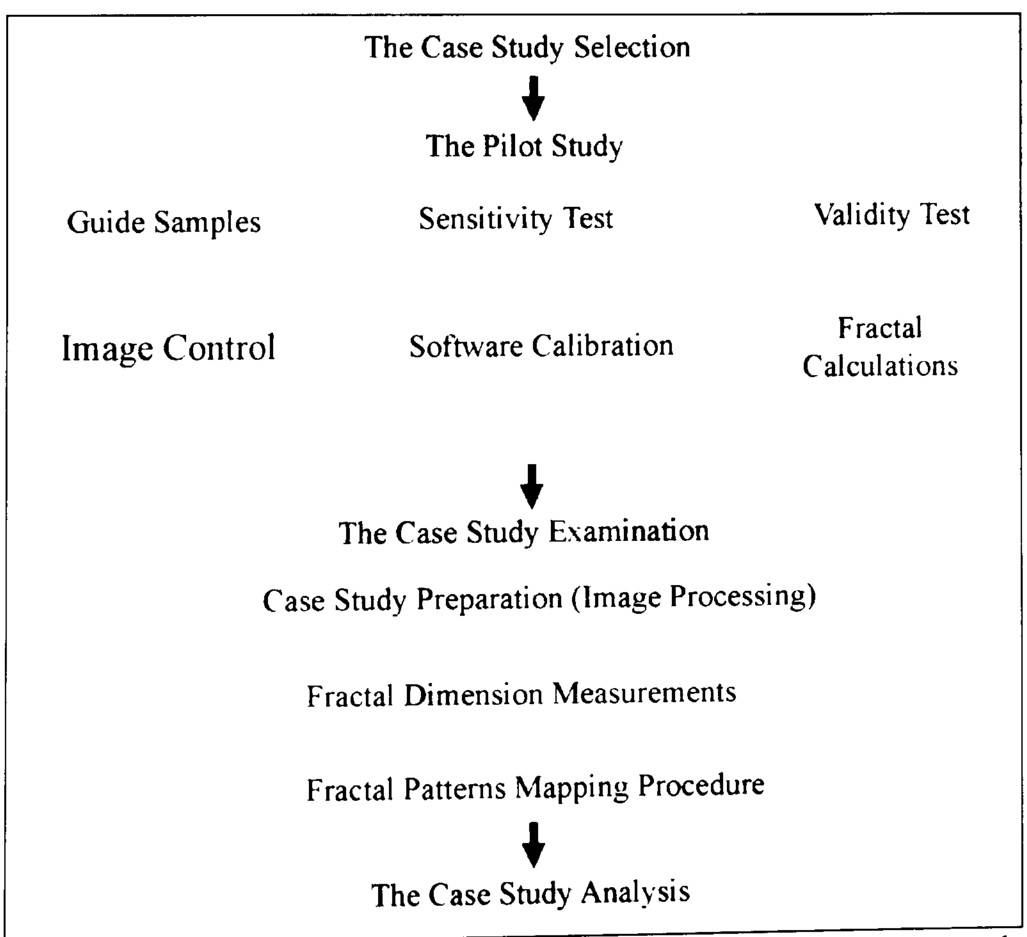


Figure 6.1: The main steps of the examination method, the pilot study and the case study examination.

As figure 6.1 shows, the method comprises two main stages: the pilot study and the case study examination. At the pilot stage, the fractal analysis software should be calibrated and the input images adjusted. At the examination stage, the fractal dimension of the selected cases will be calculated, and the result will be processed into ArcMap to be mapped (forming a fractal map). The fractal map will be produced based on the most recent aerial photos – taken in 2002 – to identify and typify fractally urban patterns within the case study. The fractal map will then provide a benchmark for data analysis in the next chapter, where the contemporary urban fractal pattern of the present will be compared to that of the past and future.

6.1.4 Advantages and limitations of using Benoit 1.3 and ArcMap 9.2

6.1.4.1 <u>Fractal analysis software, Benoit 1.3:</u>

Many fractal software programs have been developed to calculate fractal dimensions including, Benoit 1.3, FracLac 2.0, HarFa 4.9. This research has employed Benoit 1.3 due to its advantages. Firstly, the other software only uses one method for measuring the fractal dimension; while Benoit 1.3 provides multiple choices of using any of five different methods that were introduced earlier in Chapter Three (see section 3.3.5). The user can select an appropriate method depending on the particular type of data selected for analysis. For instance, the ruler method is appropriate for measuring fractal dimensions of a city boundary while box counting or mass dimension methods are more appropriate to deal with urban density or population.

Secondly, Benoit 1.3 has resolved one of the common problems that the other programs encounter when using the box counting method. The software provides an option to alter the minimum and maximum grid size depending on the subject scale. For instance, architectural scales (e.g. building elevations) and urban scales (e.g. street elevations) require different box size arrangements. The Benoit interface provides adjustable parameters, and the user should adjust them (by running a pilot test) in order to achieve an optimum result.

Thirdly, Benoit 1.3 not only measures fractal dimension but also the SD (Standard Deviation). As explained earlier in chapter three, the SD is a criterion by which a pattern composed of self-similar components can be distinguished from a pattern consisting of diverse elements. Finally, Benoit 1.3 also provides a logarithmic graph, illustrating both fractal dimensions and standard deviations.

Having explained the advantages of using Benoit 1.3, there are also some constraints as follows. Currently, none of the available software programs can measure fractal dimensions of 3D urban spatial patterns; therefore, the research is limited to two-dimensional examination and analysis of the case studies. The other constraint is that the software only performs a binary – black and white – image analysis. Therefore, some of the gray scale data information may be missed during examination. To overcome this limit, the contrast/brightness of the input images should be controlled according to the result of the pilot test to ensure that the main morphological elements – composing an urban pattern – are not missing.

The other limitation of using Benoit 1.3 is that it accepts only a bitmap image format, therefore the program cannot distinguish the difference between urban morphological and non-morphological elements in an image – for example the difference between a car and a statue. Therefore, the unnecessary data must be removed manually from an image before examination.

6.1.4.2 <u>GIS software, ArcMap 9.2:</u>

This research uses one of the latest versions of GIS software, ArcMap 9.2, due to its following advantages:

- It is capable of importing both numerical and pictorial data.
- Some data such as census, statistics and geographical data related to the selected case studies are in formats (e.g. ".shp", ".shx") which are readable by ArcGIS software.
- It has mapping capabilities by which quantitative data can be mapped.
- It has the capability of comparing different data layers according to their attributes and locations. This enables comparison of fractal data with other morphological data such as size, age, etc.

The process of importing data from Benoit software, adding attribute data, creating new shape-files, and projecting fractal maps require a number of sequential steps to be undertaken. This is a long process, difficult even for an expert operator. In this research, the process of producing a fractal map is applied to the selected cases in the north of Tehran. Application of the same method to produce a fractal map for the whole city of Tehran requires either an intermediate software program in order to process the data automatically, or a number of operators that the task can be divided between them.

6.2 Part Two: The Pilot Study

The pilot study aims to achieve two objectives: firstly, the employed fractal software, Benoit 1.3, needs to be calibrated according to the required "scales" at which the measurement will be carried out. Secondly, the aerial photos are to be tested in terms of "image resolution", "image contrast/brightness" and "image contents" in order to obtain optimum results (Figure 6.2). The latter test aims to pick appropriate morphological elements from the images and remove the elements, which may have a negative impact on the validity of the results.

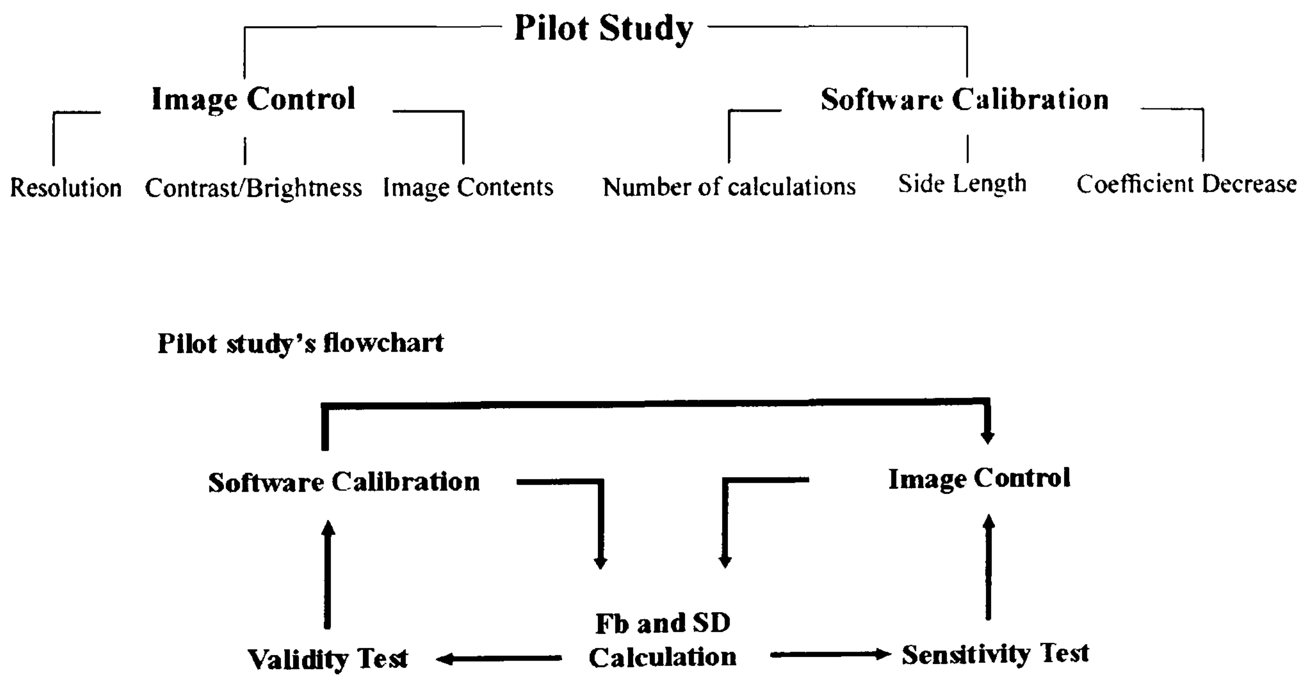


Figure 6.2: The pilot study; the steps of software and image configuration (above) and its flowchart (below).

6.2.1 Software Calibration – the validity test

A key issue for calculating fractal dimensions is the number of scale levels to be examined. As explained in chapter 3, in the case of regular fractals, calculation of fractal dimensions requires element counting of only two sequential scale levels. However, in the case of random fractals, where the fractal dimension varies at different scale levels, usually more than two scale levels are to be examined. Therefore, it is important to verify how many scale levels are required to obtain an optimum result, and which scales are more appropriate according to the research target.

As explained in Chapter Three (see section 3.3.5.1) , fractal dimensions can be calculated by the Box Counting method which requires a number of scale levels (N) of the targeted object. In the case of measuring fractal dimensions of urban patterns, this research targets neighbourhood scales. Increasing the number of scale levels (N) will focus on architectural elements (too detailed) and decreasing N will lead to the city scale levels (too large). Benoit 1.3 provides an adjustable interface to adjust the number of required scale levels required in this research. Figure 6.3 illustrates the interface of Benoit 1.3 and its adjustable parameters.

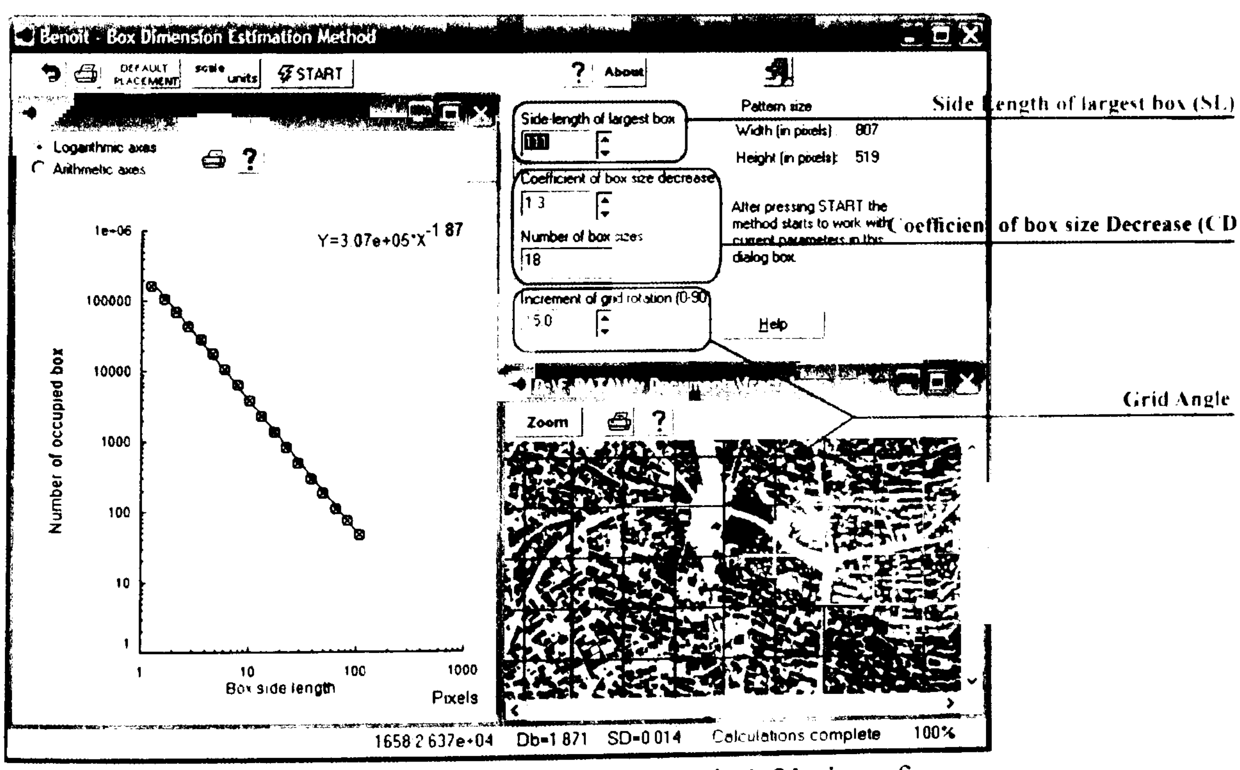


Figure 6.3: The adjustable parameters in Benoit 1.3's interface.

Benoit 1.3 provides two parameters (SL and CD) by which the number of desired scale levels of the examination (N) can be defined. The "Side Length" of the largest box (SL) can be adjusted based on the area of the examined pattern, and the smallest box is adjustable by controlling "Coefficient Decrease" of box size (CD). An appropriate combination of SL and CD will define the number of scale levels (N) to cover all desired scale levels. For instance, when SL is altered from 25 metres to 50 metres, either one more scale level will be added with a CD of 2.0; or two more scale levels will be added with a CD of 1.41.

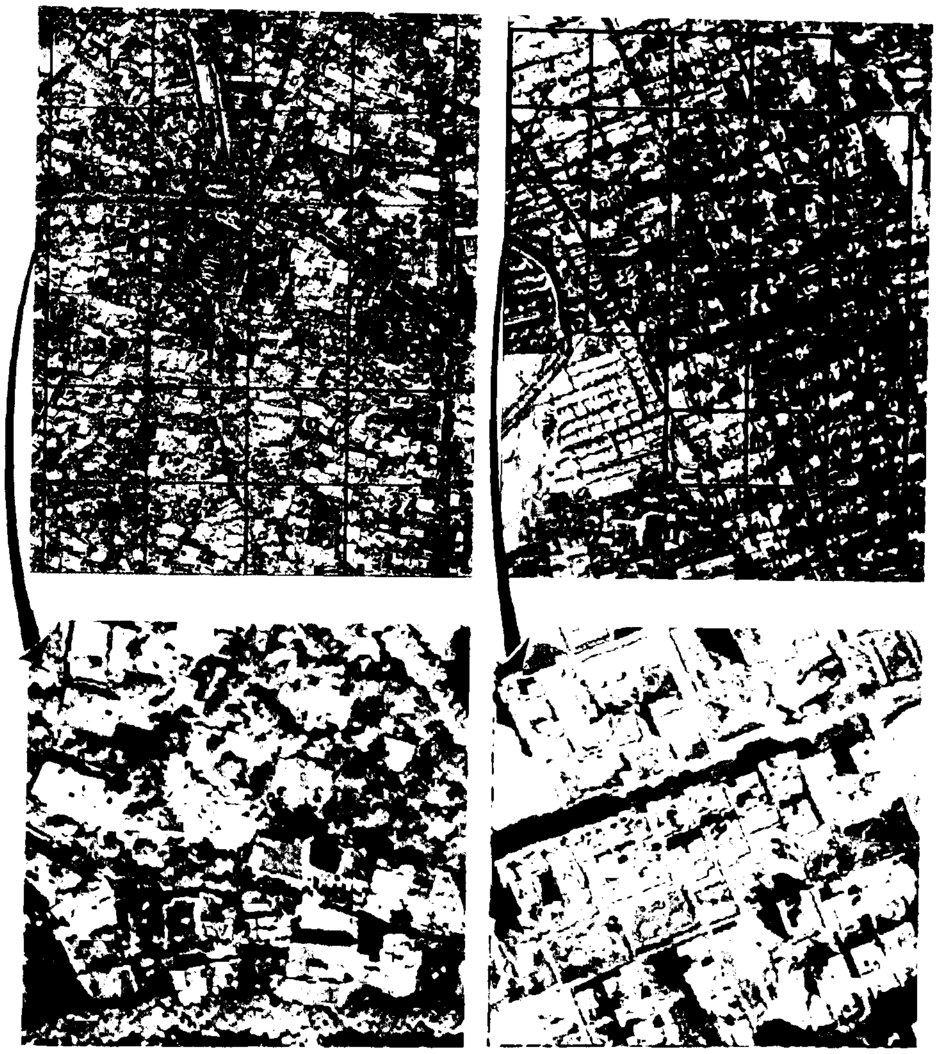


Figure 6.4: The pilot samples, neighbourhood no.5 in Tajrish (Left), and neighbourhood no.1 in Velenjak (Right). The neighbourhood area size of both cases is 200×200 metres.

Two pilot samples, one from Tajrish (the research main sample) and one from Velenjak (the research comparative sample) were selected in order to calibrate the above parameters (figure 6.4). At each step of the calibration, one of the parameters is tested by different values while the other parameter is kept constant. The pilot test was carried out on the guide samples with different possible values for SL and CD parameters. Tables 6.2 and 6.3 present the final test results.

Pilot Samples Sample 1: Tajrish N5 Sample 2: Velenjak N1	Side-Length of largest box per Pixel* (SL)	Coefficient of box size Decrease (CD)	Number of scale levels (N)	Fractal dimension box method (Fb)	Standard Deviation (SD)	Check Mark
Sample 1 Sample 2	**200**	2.0	8	**1.7147** 1.3562	**0.0507812** 0.0421610	×× ×
Sample 1 Sample 2	**100**	2.0	7	**1.8710** 1.4898	**0.0017158** 0.0954492	× ××
Sample 1 Sample 2	**50**	2.0	6	**1.8879** 1.3777	**0.0005078** 0.0423040	√ √
Sample 1 Sample 2	**25**	2.0	5	**1.8900** 1.2505	**0.0004991** 0.0080866	√ √√
Sample 1 Sample 2	**10**	2.0	4	**1.8481** 1.1542	**0.0005692** 0.0000735	√ ×
Sample 1 Sample 2	**5**	2.0	3	**1.8079** 1.1627	**0.0000788** 0.0000518	√ ×
Sample 1 Sample 2	**3**	2.0	2	**1.78847** 1.1579	**0.0000000** 0.0000000	× ××
*** Each pixel in this test is equal to one metre.**			×× Very poor, × Poor, √Acceptable, √√Good			

Table 6.2: Calibration of Fractal analysis tool; the result of the pilot test when the side-length of the largest box (SL) varies, and coefficient of box size decrease (CD) is constant.

Pilot Samples Sample 1: Tajrish N5 Sample 2: Velenjak N1	Side-Length of largest box per Pixel* (SL)	Coefficient of box size Decrease (CD)	Number of scale levels (N)	Fractal dimension box method (Fb)	Standard Deviation (SD)	Check Mark
Sample 1 Sample 2	25	**3.5**	3	**1.8960** 1.2862	**0.0001781** 0.0031649	√ ×
Sample 1 Sample 2	25	**2.5**	4	**1.8871** 1.2653	**0.0005154** 0.0067514	√ ×
Sample 1 Sample 2	25	**2.0**	5	**1.8900** 1.2505	**0.0004991** 0.0080866	√ √
Sample 1 Sample 2	25	**1.7**	7	**1.8492** 1.2141	**0.0059931** 0.0130100	√ √
Sample 1 Sample 2	25	**1.5**	8	**1.8598** 1.2472	**0.0008817** 0.0083793	√√ √√
Sample 1 Sample 2	25	**1.4**	10	**1.8761** 1.2199	**0.0021314** 0.0136986	√ ×
Sample 1 Sample 2	25	**1.3**	13	**1.8555** 1.2083	**0.0059920** 0.0144382	√ ×
*** Each pixel in this test is equal to one metre.**			×× Very poor, × Poor, √Acceptable, √√Good			

Table 6.3: Calibration of Fractal analysis tool; The result of the pilot test when the side-length of the largest box (SL) is constant, but the coefficient of the box size decrease (CD) varies.

The following factors are to be considered about the results of the tool calibration test:

1- The preliminary test carried out in Chapter Five reveals that the two selected cases morphologically consist of similar urban patterns. Therefore, the selected parameters are valid where their output demonstrates low Standard Deviation (SD).
2- The test shows for each pilot sample that the fractal dimension output (Fb) fluctuates while different parameters were tested. It can be concluded that each fractal dimension output, which is far from the mean (the average), is not valid.

Based on the above factors, the acceptable parameters were marked by the green signs (√ and √√) in the above tables and the following comments can be made:

<u>Comments on table 6.2</u>: While SL can be adjusted between 3 to 200 pixels – according to the area and the resolution of sample cases – the pilot test shows that only an SL between 3 and 50 gives valid results; and when the largest SL is equal to 25, the optimum result can be achieved. The morphological interpretation of this is that the fractal analysis of a neighbourhood area of 200metre × 200metre squares will be covered with a range grid sizes beginning with 25 metres decreasing to 0.75 metre while the coefficient decrease parameter (CD) equals 2.

<u>Comments on table 6.3:</u> CD values ranging between 1.3 to 3.5 were tested while the largest SL is 25. The best result was obtained when CD is 1.5. Morphologically, it means that the software is to be programmed to pick up elements sized between 0.75 metre and

25 metres in an urban context of 200metre × 200metre squares and to calculate the fractal dimension over 8 levels of scale with coefficient decrease scale values of 1.5.

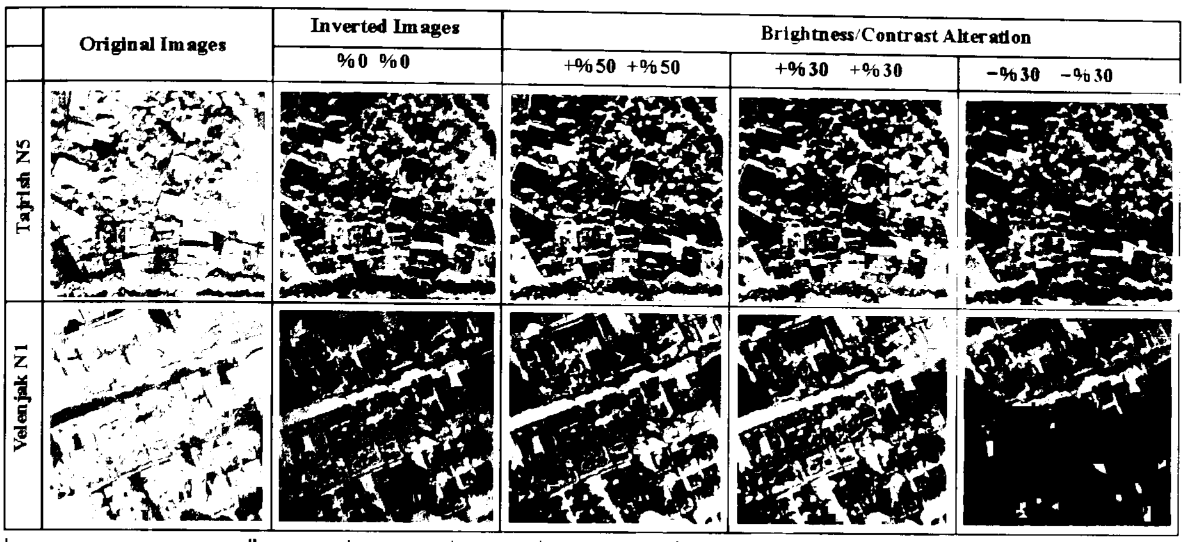
6.2.2 Image Control – the sensitivity test

The second part of the pilot study reveals that the quality and contents of input images do affect the results. Therefore, before running the main examination, all images are to be controlled in terms of the resolution, contrast, and brightness to ensure that all have the same quality and that the fractal analyser is sensitive enough to their contents. It should be noted that Benoit 1.3 recognises only white pixels as occupied boxes; therefore, all images should be inverted to negatives before being examined.

6.2.2.1 Contrast/Brightness test:

The other criteria that affect fractal calculations are the contrast and brightness of input images. The brightness/contrast of each pilot sample was adjusted by Photoshop software. As shown in table 6.4, the fractal dimensions of the samples are decreased significantly by decreasing the contrast or increasing the brightness; and inversely, their fractal dimensions are increased by increasing their contrast or decreasing their brightness.

Two factors are to be considered in order to obtain valid results; a) the maximum visibility of urban elements b) the equality of contrast/brightness for all images. The pilot test revealed that the original aerial photos have similar quality and there is no need to change their brightness/contrast. The only exceptions are the aerial photos of Tajrish for the years 1956 and 1970 in which the contrast were increased by 25% and 18% respectively to enhance their visibility to become of equal quality to the other photos.



Pilot Samples	SL	CD	N	F(b)	**Brightness** Percentage of change	**Contrast** Percentage of change	**Check Mark**
Tajrish N5	25	1.5	8	1.7867	-%30	-%30	×
				1.6027	%0	-%30	××
Velenjak N1	25	1.5	8	1.2106	-%30	-%30	×
				1.1674	%0	-%30	××
Tajrish N5	25	1.5	8	1.8598	%0	%0	√√
				1.9243	%0	+%50	××
				1.5805	+%50	%0	××
Velenjak N1	25	1.5	8	1.2472	%0	%0	√√
				1.4936	%0	+%50	××
				1.0966	+%50	%0	××
Tajrish N5	25	1.5	8	1.8879	+%30	+%30	√
				1.7185	+%30	%0	××
Velenjak N1	25	1.5	8	1.2889	+%30	+%30	√
				1.1571	+%30	%0	×
×× Very poor, × Poor, √Acceptable, √√Good							

Table 6.4: The pilot test; the sensitivity to the changes in the contrast/brightness of the pilot images.

6.2.2.2 <u>Resolution test:</u>

The aerial photos used for the pilot test provide resolutions up to 400 pixels per the area of each neighbourhood (200metre × 200metre squares) equal to two pixels per metre. In other words, the fractal analysis tool can identify any elements with 50centimetre × 50 centimetre squares size or larger. This level of resolution may also be problematic because the elements which are not considered as morphological (e.g. people walking in the streets) will be processed by the software while counting the occupied boxes. Table 6.5 shows the impact of changing the resolution of pilot samples on the calculation of its fractal dimension.

Pilot Samples	SL	CD	N	F(b)			
				100 x 100 1pxl=2m	200 x 200 1pxl=1m	300 x 300 1pxl=0.75m	400 x 400 1pxl=0.5m
Tajrish N5	25	1.5	8	1.7014	1.8598	1.8942	1.9142
Velenjak N1	25	1.5	8	1.1238	1.2472	1.3401	1.4101

Table 6.5: the pilot test, the sensitivity to image resolutions. The acceptable resolution is in the grey box.

The resolution of one pixel per square metre will cover main morphological elements existing at neighbourhood scale (as presented earlier in table 6.1). At this level of resolution, the non-morphological elements, those of lengths lower than one metre, will not be visible; this reduces their negative impact. However, this level of resolution does not reduce the negative impact of the existing vehicles, and therefore, they are to be removed manually from the images.

6.2.2.3 Contents test:

Benoit 1.3 analyses binary black and white images and therefore cannot automatically pick up the targeted elements from a gray scale image. Therefore, the contents of all images must be controlled to ensure that built-up spaces are not mixed up with open spaces. The roads, outdoor parking spaces, and swimming pools in black and white image format are represented by black pixels similar to buildings. However, these elements are part of open space patterns not built-up urban patterns. Therefore, these elements are to be inverted to white pixels similar to other open spaces to avoid misinterpretation during the research analysis.

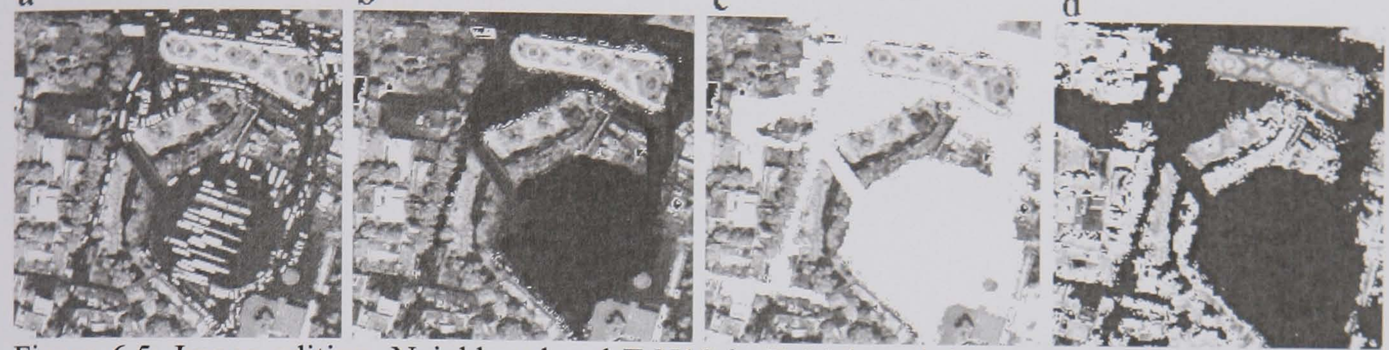


Figure 6.5: Image editing. Neighbourhood T-N10 in Tajrish and the steps of adjustments of its contents; a) original aerial photo, b) vehicles removal and element match, c) road inversion, d) image inversion.

Table 6.6 presents the result of tests before and after content adjustment for the pilot samples. Neighbourhood no.10 of Tajrish (figure 6.5) contains the main bus terminal in the north of Tehran and one of the major roads passes through it, and therefore, it was added to the pilot samples to be tested.

Pilot Samples and Tajrish N10	**SL**	**CD**	**N**	**F(b)**	**SD**	**Check Mark**
Tajrish N5 before contents adjustment	25	1.5	8	1.8598	0.0008817	×
Tajrish N5 after contents adjustment	25	1.5	8	1.8329	0.0008712	√
Velenjak N1 before contents adjustment	25	1.5	8	1.2472	0.0083793	×
Velenjak N1 after contents adjustment	25	1.5	8	1.2166	0.0076443	√
Tajrish N10 before contents adjustment	25	1.5	8	1.7296	0.0031395	××
Tajrish N10 after contents adjustment	25	1.5	8	1.5366	0.0026130	√√

Table 6.6: the pilot study – contents test. Road and parking spaces are inverted to white pixels indicating that they are part of the neighbourhoods' open spaces.

The pilot test reveals that roads and streets, as part of an urban pattern have great influence on the fractal dimensions; but should be adjusted to be accounted as part of urban open space in order to obtain more accurate results. The importance of the content adjustment is more obvious in neighbourhood no.10, which contains a main road and a large-scale bus terminal (figure 6.5).

6.3 Part Three: The Case Study Examination

This part comprises case studies' preparation, fractal dimension measurement, and mapping fractal dimensions. The main objective of this part is to create fractal maps for the research case studies including Tajrish as the main sample case and Velenjak as its comparator. Figure 6.6 illustrates the sequence of image/data processing in order to produce fractal maps.

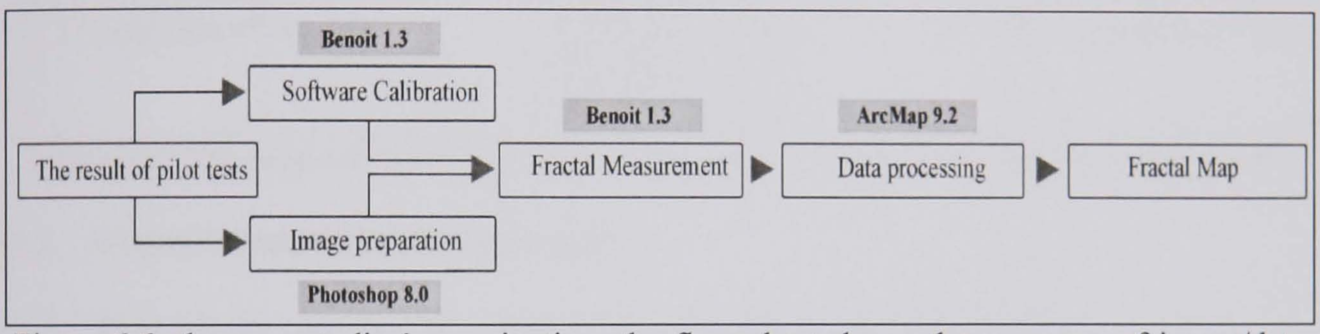


Figure 6.6: the case studies' examination; the flow chart shows the sequence of image/data processing at each steps and the employed software programs.

6.3.1 Case studies' preparation and image processing

The aerial photos related to the case studies are prepared for actual examination according to the suggestions made by the pilot study. The images are processed using the three following stages (figure 6.7). Firstly, all input images are to be controlled in terms of resolution and contrast\ brightness as discussed in sections 6.2.2.1 and 6.2.2.3. Secondly, the vehicles should be removed from the images and the open space elements (e.g. roads, streets) are to be merged into one layer in white as explained in section 6.2.2.3. At this stage, also, all images should be inverted to negatives, because Benoit 1.3 considers white pixels as occupied boxes and count them against the black pixels in the process of fractal dimension calculation (see also figure 6.5). Thirdly, aerial photos like any other kind of photos are usually out of scale. The ArcGIS-software has a geo-referencing tool by which the aerial photos of the selected case studies (Tajrish, and Velenjak) can be resized to fit into the scaled map of these areas (as a valid point of reference). This assists defining metrically the size of each neighbourhood unit, and to divide the aerial photos to 24 equal 200metre × 200metre square (see also figure 6.4). Figure 6.7 illustrates clearly the sequential steps undertaken at each stage.

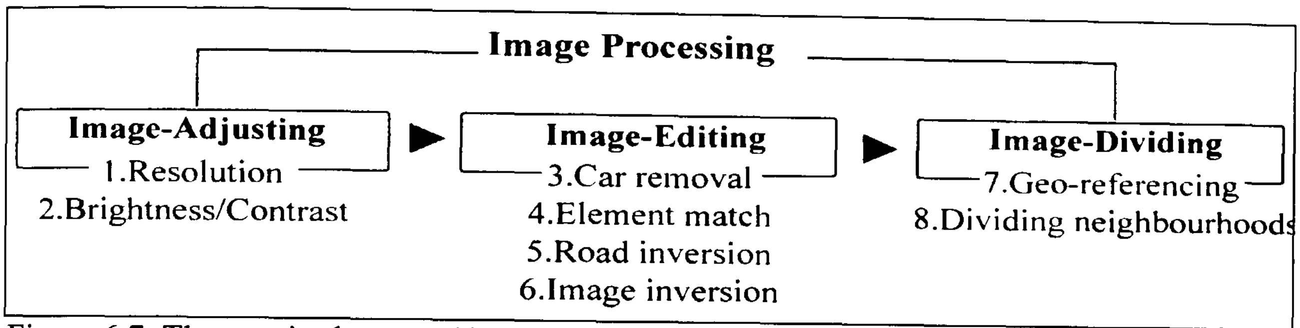


Figure 6.7: The required steps of image processing according to the results of the pilot study.

6.3.2 Fractal dimension measurement

6.3.2.1 Experiment one (fractal assessment at the neighbourhood scale):

Having calibrated the fractal analysis software – according to the result of the pilot tests – the fractal dimension (Fb) of each neighbourhood can be measured. Tables 6.7, and 6.8 show the result of fractal dimensions measured for 24 neighbourhoods of Tajrish and Velenjak respectively.

Neighbourhood ID	**T-N1**	**T-N2**	**T-N3**	**T-N4**	**T-N5**	**T-N6**	**T-N7**	**T-N8**
Fractal Dimension (Fb)	**1.8502**	**1.7239**	**1.7458**	**1.7898**	1.7329	**1.7016**	**1.7460**	**1.7554**
Standard Deviation (SD)	0.001997	0.000434	0.001787	0.000881	0.000871	0.000307	0.001886	0.000936
Neighbourhood ID	**T-N9**	**T-N10**	**T-N11**	**T-N12**	**T-N13**	**T-N14**	**T-N15**	**T-N16**
Fractal Dimension (Fb)	**1.7758**	**1.5366**	**1.7106**	**1.6346**	**1.7593**	**1.7808**	**1.7882**	**1.7846**
Standard Deviation (SD)	0.001656	0.002613	0.000151	0.003155	0.001956	0.001589	0.001871	0.004460
Neighbourhood ID	**T-N17**	**T-N18**	**T-N19**	**T-N20**	**T-N21**	**T-N22**	**T-N23**	**T-N24**
Fractal Dimension (Fb)	**1.7500**	**1.7849**	**1.7567**	**1.7751**	**1.7768**	**1.7141**	**1.7388**	**1.6996**
Standard Deviation (SD)	0.001678	0.001053	0.006038	0.002449	0.000408	0.005234	0.000418	0.000576
The average for ($\overline{F_b}$) **and** ($\overline{SD}$)	$\overline{F_b} = \sum_{n=1}^{24} \frac{(Fb)_n}{N} = 1.7421$				$\overline{SD} = \sum_{n=1}^{24} \frac{SD_n}{N} = 0.001850$			

Table 6.7: Fractal calculation at neighbourhood scale of Tajrish, neighbourhood area size 200m×200m squares. The aerial photos of year 2002 were used for this examination.

Neighbourhood ID	V-N1	V-N2	V-N3	V-N4	V-N5	V-N6	V-N7	V-N8
Fractal Dimension (Fb)	**1.2166**	**1.2394**	**1.3345**	**1.3882**	**1.2583**	**1.1911**	**1.3338**	**1.3897**
Standard Deviation (SD)	0.007644	0.003876	0.003183	0.000548	0.000142	0.002920	0.003211	0.010245
Neighbourhood ID	**V-N9**	**V-N10**	**V-N11**	**V-N12**	**V-N13**	**V-N14**	**V-N15**	**V-N16**
Fractal Dimension (Fb)	**1.4275**	**1.3680**	**1.4048**	**1.4511**	**1.3547**	**1.4590**	**1.4225**	**1.5321**
Standard Deviation (SD)	0.004830	0.001143	0.000281	0.000677	0.002934	0.005923	0.010325	0.000297
Neighbourhood ID	**V-N17**	**V-N18**	**V-N19**	**V-N20**	**V-N21**	**V-N22**	**V-N23**	**V-N24**
Fractal Dimension (Fb)	**1.5261**	**1.2612**	**1.4277**	**1.3785**	**1.1516**	**1.1898**	**1.3065**	**1.3938**
Standard Deviation (SD)	0.005769	0.000841	0.003318	0.000252	0.000104	0.000405	0.000698	0.000884
The average for ($\overline{F_b}$) **and** ($\overline{SD}$)	$\overline{F_b} = \sum_{n=1}^{24} \frac{(Fb)_n}{N} = 1.3245$				$\overline{SD} = \sum_{n=1}^{24} \frac{SD_n}{N} = 0.002935$			

Table 6.8: Fractal calculation at neighbourhood scale of Velenjak, neighbourhood area size 200metre×200metre squares. The aerial photos of year 2002 were used for this examination.

6.3.2.2 Experiment two (fractal assessment at the local scale):

In another experiment, if the fractal assessment is carried out at the local scale rather than neighbourhood scale, then the results will be as shown in table 6.9. In this experiment, the fractal dimensions and the standard deviations measured (Fb and SD in table 6.9) are higher than the average of these values measured in the first experiment ($\overline{F_b}$ and $\overline{SD}$ in tables 6.7 and 6.8).

The research case studies	SL	CD	N	F(b)	SD
Tajrish	250	1.5	8	**1.8047**	0.030144
Velenjak	250	1.5	8	**1.4659**	0.007985

Table 6.9: Fractal dimensions measured at local scales (the area size of 1200metre×800metre squares) for Tajrish and Velenjak using the aerial photos of the year 2002.

The initial comments on tables 6.7, 6.8, and 6.9 are as follows. Firstly, in both experiments (both at local and neighbourhood scales), the measured fractal dimensions for Tajrish are higher compared to those for Velenjak. In other words, the gradual development or the organic urban pattern of Tajrish demonstrates a higher degree of physical complexity than the newly developed and planned pattern of Velenjak (see also figure 6.8). Secondly, the difference between Fb and $\overline{F_b}$ – measured in the above experiments – implies that macro scales have a higher degree of complexity than micro scales. In other words, the fractal dimensions – as the mathematical indicators of physical complexity – increase while zooming out from architectural scales to city scales.

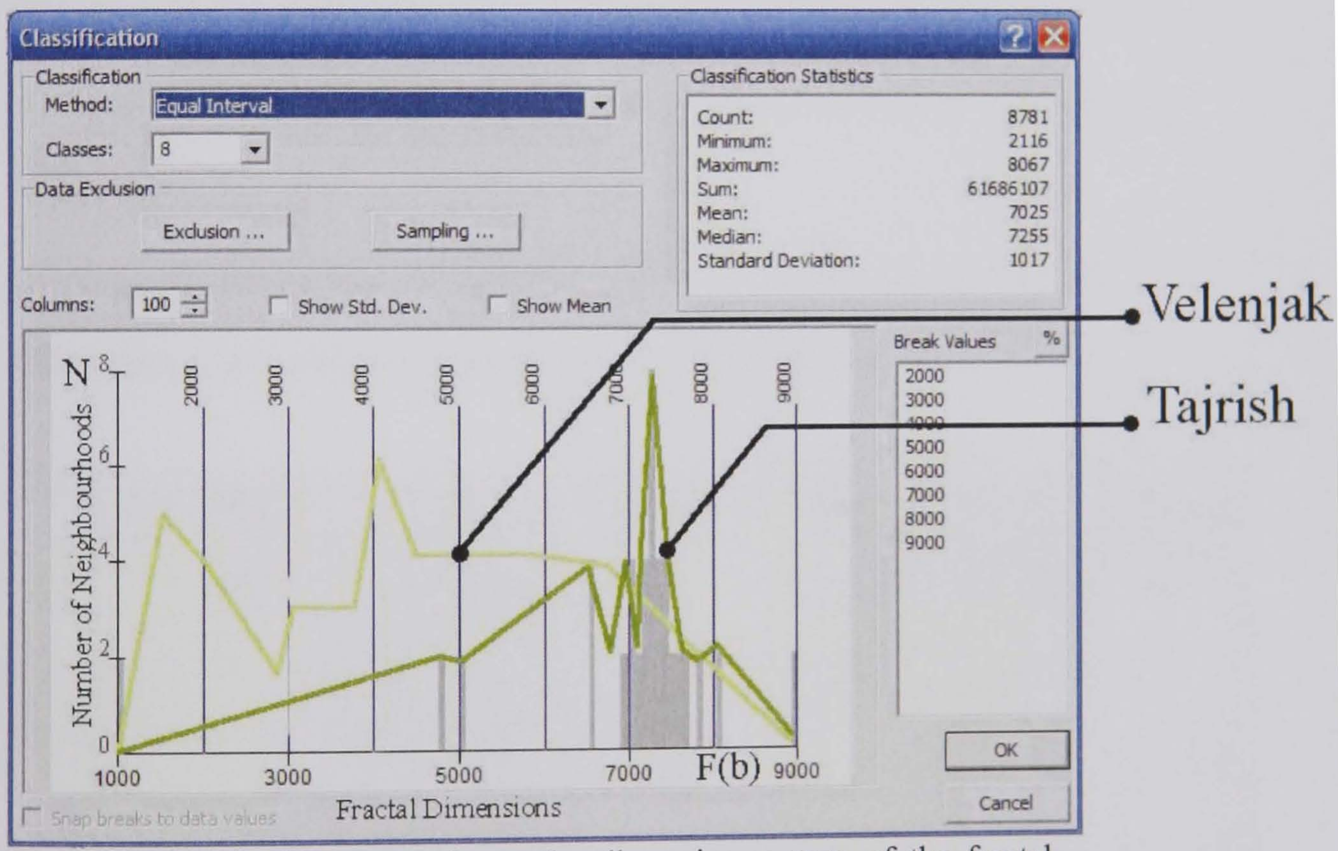


Figure 6.8: The histogram shows the dispersion pattern of the fractal dimensions assessed for the neighbourhoods in Tajrish as compared to Velenjak.

6.3.3 Mapping fractal dimensions, data processing to fractal maps

While the numbers in the previous tables might seem complicated or difficult to compare, converting them to a range of colour scales and creating fractal maps provides a much clearer basis for pattern analysis and comparison. The ArcGIS software has mapping capabilities enabling quantitative data to be converted to pictorial data.. The research carried out the following steps to create fractal maps:

1- Creating a new shape file: A new morphological layer in the format of new shape files (.shx) were created equal to the case study area sizes.

2- Dividing the shape: Each shape-file was divided into 24 equal 200metre × 200metre square subdivisions.

3- Assigning fractal attributes to the shape file: the fractal attribute, as a new feature, was assigned for each subdivision by transferring the fractal dimension data from Benoit 1.3 to the new created shape file in ArcMap 9.2 (figure 6.9).

4- Mapping the fractal data: the fractal attributes were added to the existing parcel data layer, which contains morphological data (figure 6.10).

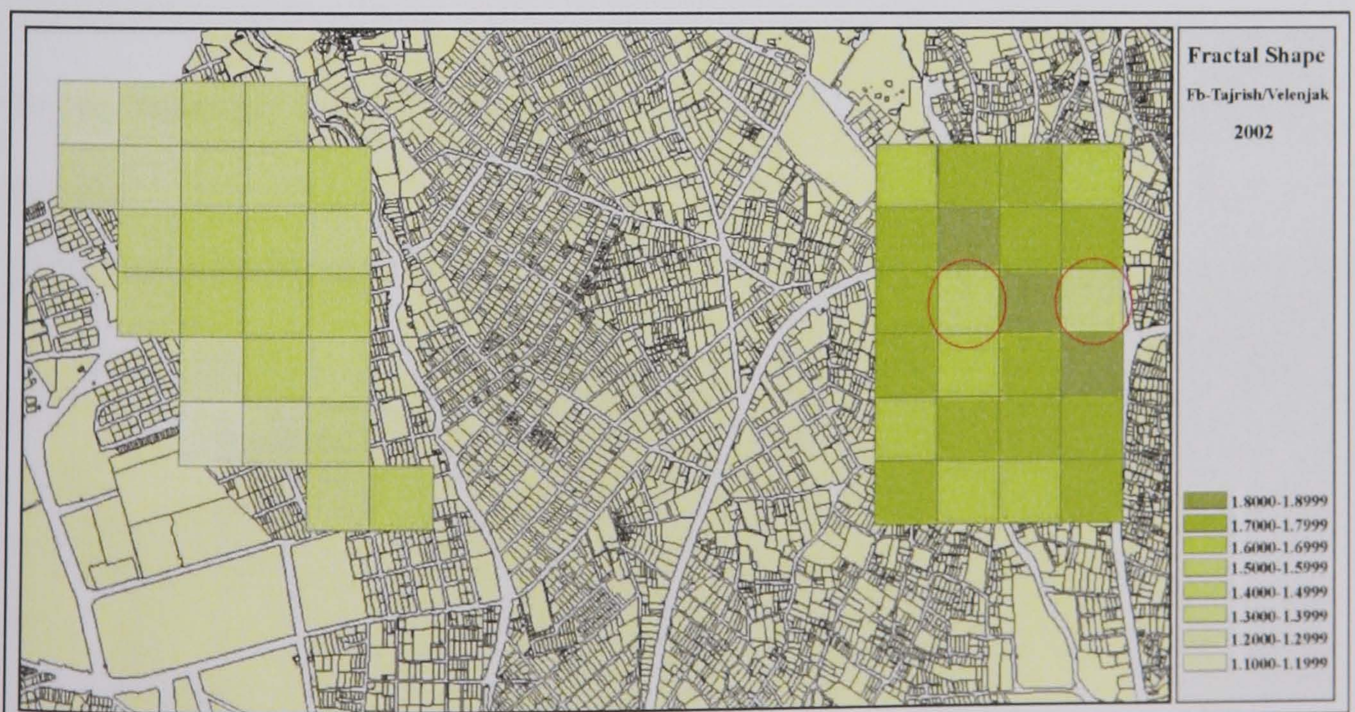


Figure 6.9: Fractal shapes created for Velenjak (left) and Tajrish (right). They have been created by converting quantitative data to pictorial data by ArcGIS software. Tajrish neighbourhoods, as compared to Velenjak, demonstrate higher fractal dimensions except the areas that marked with red circles.

Figure 6.10: The fractal map of Velenjak (left) and the fractal map of Tajrish (right) for the year 2002.

Having carried out the above steps, the fractal maps were produced for the research sample cases (Tajrish and Velenjak). Steps one to three explain how 'the fractal shapes' were created (figure 6.9); and step four indicates how these shapes were converted to fractal maps (figure 6.10). It should be emphasised that the fractal dimensions have been calculated by neighbourhood, not by plot. Therefore, both figures 6.9 and 6.10 represent fractal dimensions at the neighbourhood level, however the latter is the map version of the first.

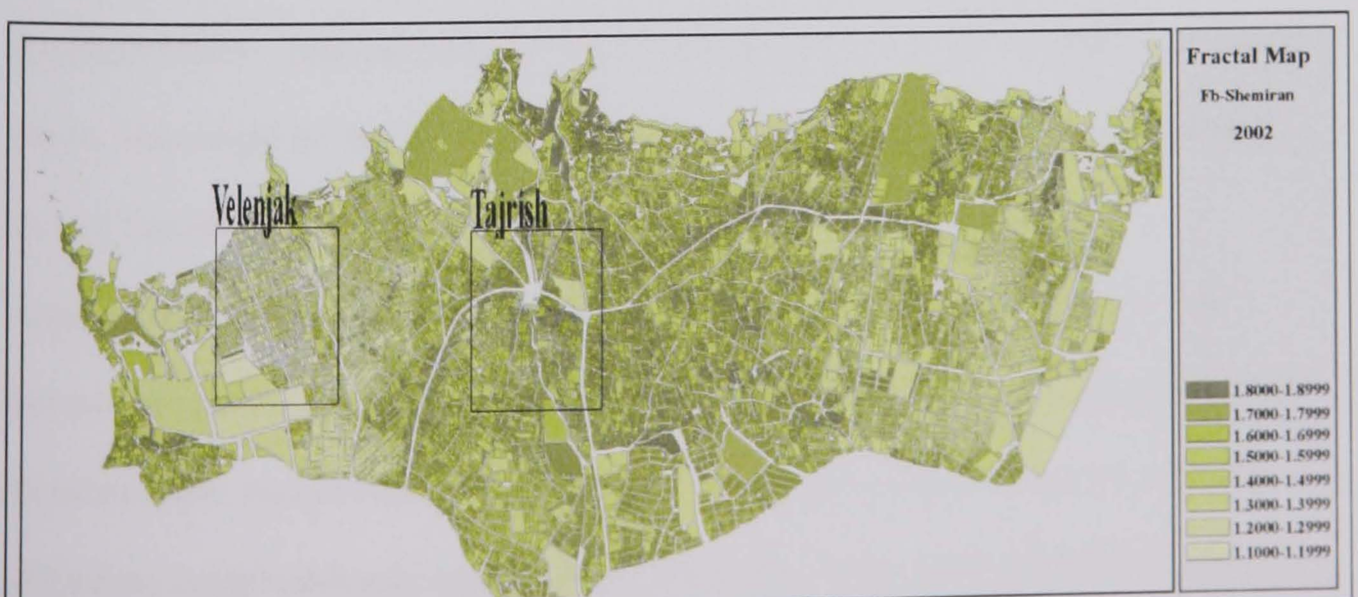


Figure 6.11: The fractal map of Shemiran for 2002 including the fractal urban patterns of the sample case studies, Tajrish and Velenjak, with their fuzzy boundaries.

The same method can be applied to produce a fractal map for the whole district of Shemiran and even for the entire city of Tehran. Figure 6.11 illustrates the first fractal map produced at the district scale based on the aerial photos of 2002. Having produced the fractal maps for the case studies, the following initial comments can be made. As figure 6.10 illustrates, the examined neighbourhoods in Tajrish generally have higher fractal dimensions than those in Velenjak. In other words, the urban patterns of Tajrish demonstrate significantly a higher complexity than those of Velenjak. This conforms to the research assumption that organic patterns are more complex than planned patterns. The observation also suggests that the areas around the centre of old neighbourhoods have generally high fractal dimensions. This implies that the older is more complex (see figure 7.9 in the next chapter). The observation also reveals that parks and gardens demonstrate higher fractal dimensions (see also section 7.3.3 in the next chapter).

The fractal shapes created for the neighbourhoods of Tajrish indicate generally high complexity with two exceptions. The fractal dimensions assessed for two neighbourhoods – marked with red circles in figure 6.9 – are low in comparison to the others. This might be due to recent large-scale urban interventions and developments around Tajrish Square such as the bus terminal, car parking (see figure D.2a, Appendix D), and the recent regeneration plan for the sites close to the shrine of Imamzadeh Saleh. As figure 6.11 shows, the fractal patterns of the neighbourhoods in Shemiran have fuzzy boundaries. It means that it is impossible to draw precise lines around the neighbourhoods with the same physical complexity (see Chapter Seven, section 7.2.1 and figures 7.5, 7.6 and 7.7).

Further to the above initial comments, fractal maps reveal other valuable information for analysing urban morphological features including urban patterns. They can be used for pattern identification, comparison, and classification. The fractal map also provides the basis for measuring the changes occurring in urban patterns over time. These issues will be elaborated at the research analytical stage in the next chapter.

6.4 Chapter Summary

The chapter demonstrated both mathematically and graphically the degree of physical complexity of urban patterns in Tehran. Fractal examination of the selected case studies reveals that fractal dimension is a sensitive criterion showing mathematically the degree of urban physical complexity. This chapter also developed a fractal assessment technique to illustrate such a complexity in a map format (the fractal map). The fractal calculation software (Benoit 1.3) and the GIS software (ArcMap 9.2) were linked to produce the fractal maps of the case studies. The advantages and limitations of using each software were identified. The method of the fractal examination was tested and the steps of data processing, image processing, the preparation the fractal analysis tool (software calibration) and finally, the fractal examination of the case study was carried out in order to produce the fractal map (figure 6.12).

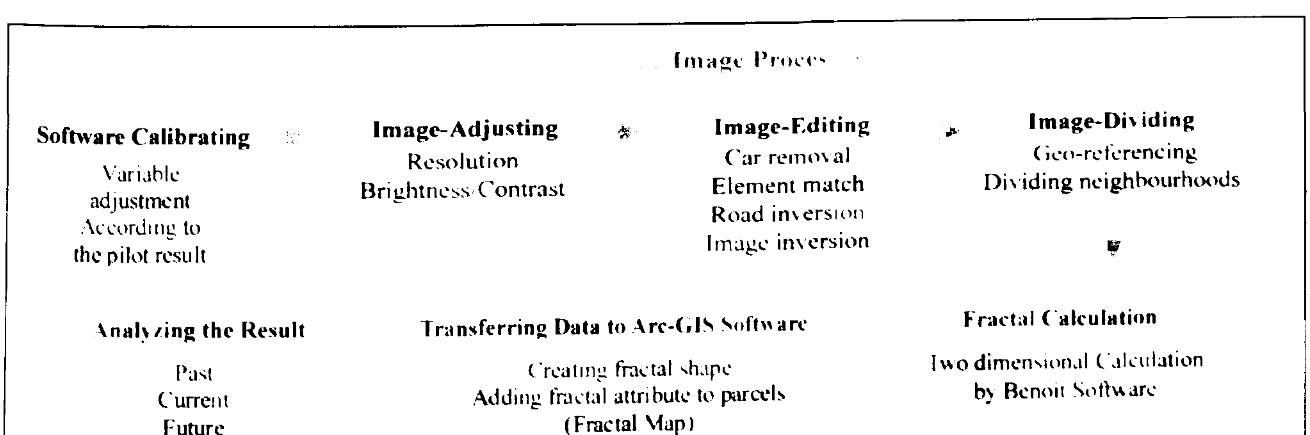


Figure 6.12: The summary of the sequential steps explained in this chapter to produce the fractal map.

Therefore, the chapter achieved its main goal of devising a fractal analysis technique to produce the fractal maps of the selected case studies. The maps explicitly show the differentiation in physical complexity that is exhibited by different patterns of growth. The organic pattern of Tajrish was found to have considerably higher fractal dimensions than the planned pattern of Velenjak. This supports the assumption that time plays an important role in increasing complexity (see the conclusion of Chapter Four). In other words, the older urban areas that gradually evolved are expected to be more complex than the areas that rapidly developed. In the next chapter, the result of the case study examination will be analysed in further detail.

CHAPTER SEVEN

FRACTAL ANALYSIS OF THE CASE STUDY
AND
INTERPRETATIONS

Introduction:

Fractal dimension assessment of the urban environment provides a mathematical method for spatial quantitative analysis. The fractal maps created in the previous chapter facilitate spatial analysis and suggest a new approach to urban pattern recognition in terms of fractal identification and classification. Fractal maps also provide the basis for more precise measurement of the degree of change that an urban pattern experiences over time. In Chapter Seven, the result of the case study examination will be analysed and the complexity of the urban patterns will be fractally interpreted. Figure 7.1 illustrates the structure of the issues that will be discussed in this chapter.

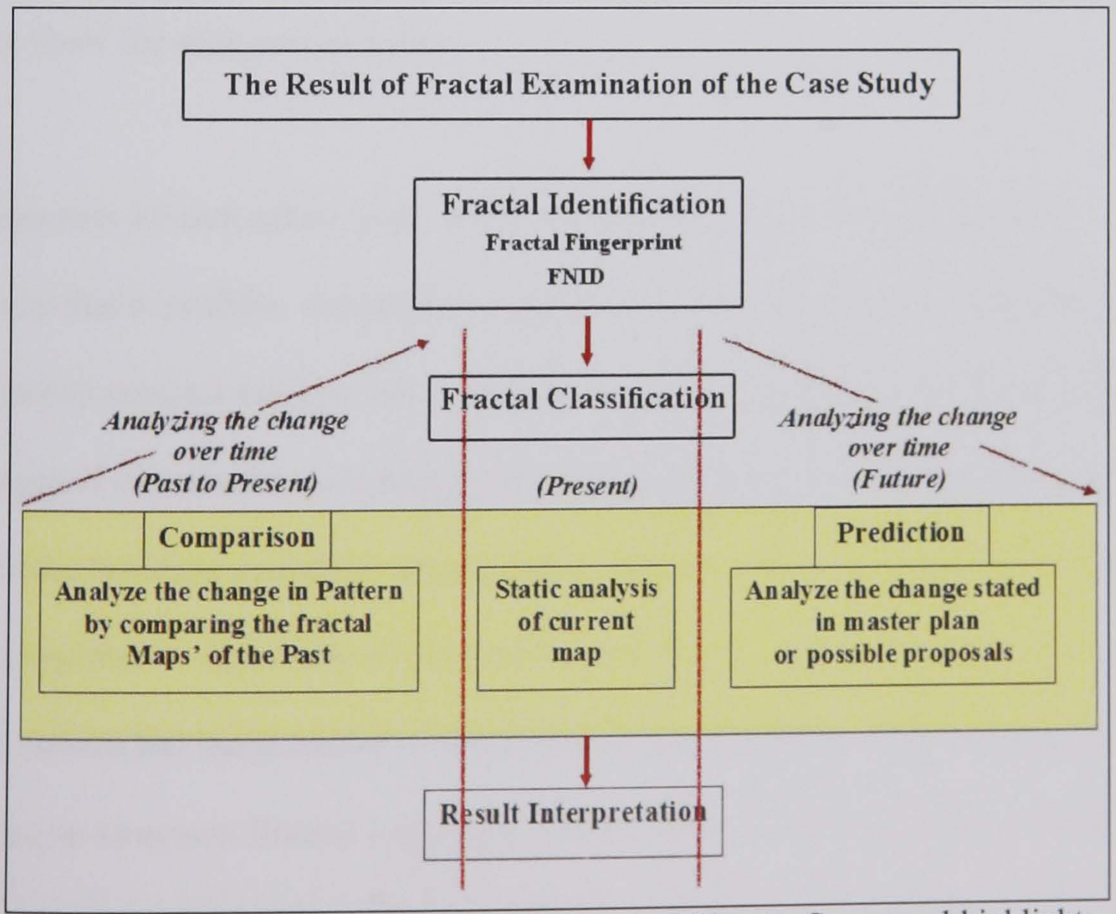


Figure 7.1: the diagram shows the structure of Chapter Seven and highlights the main subjects.

7.1 Part One: Fractal identification of urban patterns

7.1.1 Fractal map as an urban fingerprint

Urban morphologists study 'the physical (or built) fabric of urban form, and the people and processes shaping it' (Larkham, 1991, p.55; see also Larkham, 2004b). The concept of urban fingerprints is based on the idea that correlation between urban form and people (socio-spatial processes) will result in a unique form for each part of a city. From a morphological point of view, although the nature of this correlation varies from case to case, the behaviour of agents of urban change determines how an organizational relationship is constructed between each basic urban unit and its neighbourhoods at local levels and with other parts of a city at macro levels. Such processes are unpredictable (as discussed in Chapter Three), and differ from case to case, which consequently results in 'a unique form' for each part of a city.

The uniqueness of each urban form can be identified by measuring the level of complexity that it exhibits. Aerial photos used as a means of remote sensing data for textural urban analysis can provide a vast amount of information about underlying morphological complexity including building density, street frequency, street size, characteristic building materials, density, type, clustering of vegetation, etc, which can be analysed together or separately at any required city scale. Fractal dimension analysis of an urban pattern has the potential to identify mathematically the level of complexity underlying its structure. Fractal maps demonstrate visually such complexity, and therefore, can be considered as a kind of urban morphological fingerprint.

During the last two decades, a number of attempts have been made to identify a kind of fingerprint or textural signature for city patterns similar to DNA in biology. Some of these approaches have focused on coding the elements that constitute socio-economic patterns (e.g. Dodge and Kitchin, 2005) and some have emphasized physical features of urban patterns (e.g. Webster, 1995; Steadman, 2008). It can be argued that the latter approach might better represent city identity. For example, urban morphological categories will be defined by housing density better than population density. The reason should be obvious, as population density could vary between neighbourhoods of the same housing density. Webster (1995, p.295) writes:

> 'The urban feature defined by its physical elements, might better represent city identity than the one defined by its underlying social elements' (Webster, 1995, p.295).

The approaches to morphological pattern identification also fall into two groups: structural and statistical. The structural methods are based on the idea that urban patterns comprise some simple shapes. The composition or reoccurrence of these primitive shapes can produce different pattern types (see Lynch, 1981; Marshall, 2005). While planned or semi-planned patterns can be identified by structural methods, they cannot easily distinguish differences between various patterns that can be classified under the term organic. However, statistical methods seem to have fewer restrictions as they are mainly based on mathematical interpretation of urban forms and patterns. Marshall (2005) provides examples of both methods with an emphasis on the first group.

In this sense, the fractal assessment technique developed in this research to produce fractal maps can be categorised as a statistical method. Moreover, it is close to the technique employed by Webster (1995) who also used aerial photos for textural quantitative analysis. The fractal maps of the case study of Shemiran and sample cases of Tajrish and Velenjak (see figures 6.10 and 6.11 in Chapter Six) have been produced based on the unique structural properties of their neighbourhood units; therefore, like other textural analysis methods, they can be thought of as a kind of morphological fingerprint. However, the advantage of the fractal fingerprints suggested in this research over other approaches (including the one suggested by Webster, 1995) is that the other statistical approaches are usually limited to one particular morphological property and restricted to only one specified urban scale, while the fractal approach is more general.

7.1.2 Fractal Neighbourhood Identification code (FNID)

The method developed to produce the fractal map (see Chapter Six, section 6.3.3) can be shortened and amended in order to create a unique Fractal Neighbourhood Identification code (FNID) for each neighbourhood. Having assessed the fractal dimensions of the neighbourhoods in Tajrish, there is no need to convert them to pictorial data. Instead, fractal dimensions at local, district, and city scales are to be examined and added to the fractal dimension of each neighbourhood (figure 7.2). The fluctuation of fractal dimensions in table 7.1 indicates that the urban patterns at different scales of the city are not self-similar; in other words, the patterns demonstrate different degrees of physical complexity at different scales of the city hierarchical structure (compare with figure 3.25, in Chapter Three).

Box size	**1**	**5**	**10**	**20**	**35**	**50**	**75**	**100**
Scale of test	1 pixel = 100x100 metres	1 pixel = 500x500 metres	1 pixel = 1000x1000 metres	1 pixel = 2000x2000 metres	1 pixel = 3500x3500 metres	1 pixel = 5000x5000 metres	1 pixel = 7500x7500 Metres	1 pixel = 10000x10000 metres
F(b)	**1.6527**	**1.6934**	**1.8125**	**1.7910**	**1.7690**	**1.7015**	**1.5923**	**1.6810**

Table 7.1: Estimating the fractal dimension of Tehran by fixing the input image size varying the scale of the city.

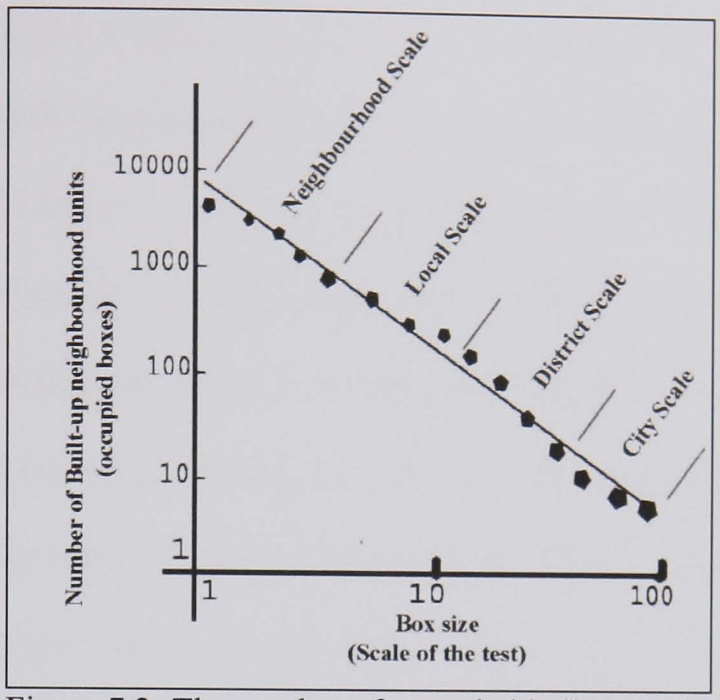


Figure 7.2: The number of occupied built-up units (defined by occupied pixels) in Tehran's aerial photo (2002) at different scales (defined by box size) calculated by Benoit Software 1.3 (box counting method).

Figure 7.2 plots the number of occupied pixels, as representative of built up areas, on a graph of which different city scale levels (the horizontal axis) is illustrated. The slope of the resulting line of the graph is the average fractal dimension assessed for the city hierarchical structure at its different scale levels. As shown in table 7.1, the F(b) is changed when the measurement is carried out at different scales.

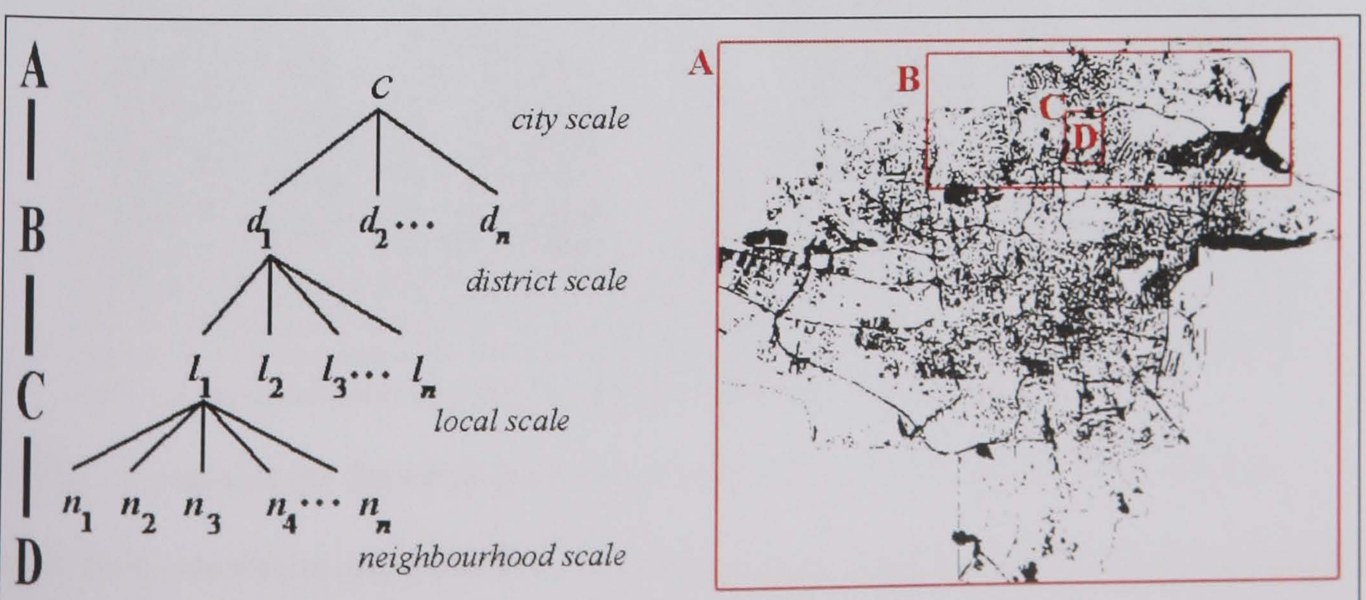


Figure 7.3: The hierarchical logic behind FNIDs and the number of neighbourhoods participating at each level of calculation.

The complexity of a single neighbourhood varies if that neighbourhood is observed at different scale levels of the city hierarchical structure. For instance, the complexity of neighbourhood T-N11 (figures 7.3 and 7.4, D) in Tajrish is 1.7106 (Fb) if measured at a local level where there are only 24 other neighbourhoods participating in calculations, and Fb is 1.7562 if measured at district level (Shemiran, figure 7.4, B) where so many other neighbourhoods are added. In the same way, the scale ranges for varying fractal dimensions over the city must take many local areas per district, and many neighbourhoods per district, and so on (figures 7.3 and 7.4, A).

Figure 7.4: Fb measured for Tehran at different scales; A) The city scale, B) The district scale, C) the local scale, and D) the Neighbourhood Scale. (Haghani, 2004, p.7)

Table 7.2 contains the fractal dimensions assessed for different scale levels, resulting from each calculation using the Box Counting method. The Benoit software presents the average dimension as its main output, which in this case of the Tehran city scale, would be 1.6918. F(b) can be measured for district, local and neighbourhood scales (shown in Figure 7.4 and table 7.2) if their respective images is used as input data.

Scale Level of Calculation	Fb	Scale Level of Calculation	Fb
Whole Tehran	1.6918	Shemiran, the north of Tehran	1.7562
Tajrish	1.8047	Neighbourhood no.11 in Tajrish	1.7106

Table 7.2: The assessed fractal dimensions for the different scale levels of the city of Tehran.

The sequence of assessed fractal dimensions from the neighbourhood to the city scales can creates a unique FNID for Tajrish-N11. In the case of 2D image analysis, the fractal dimensions are always more than 1.0000 and less than 1.9999, therefore FNID can be created with the decimal numbers as shown below:

A	-	B	-	C	-	D
6918		7562		8047		7106

A FNID contains 16 digits in four sequential sections, A-B-C-D, where each part demonstrates the city ID, the district ID, the local ID, and the neighbourhood ID respectively. In the same way, FNIDs of other neighbourhoods can be calculated. Table 7.3 and 7.4 show the results for 8 sample neighbourhoods, 4 in Tajrish and 4 in Velenjak.

Selected Neighbourhoods in Tajrish	T-N1	T-N10	T-N11	T-N15
FNID	6918-7562-8047-8502	6918-7562-8047-5366	6918-7562-8047-7106	6918-7562-8047-7882

Table 7.3: FNIDs of the neighbourhoods T-N1, T-N10, T-N11, and T-N15 in Tajrish.

Selected Neighbourhoods in Velenjak	V-N1	V-N12	V-N19	V-N23
FNID	6918-7562-4659-2166	6918-7562-4659-4512	6918-7562-4659-4277	6918-7562-4659-3065

Table 7.4: FNIDs of the neighbourhoods V-N1, V-N12, V-N19, and V-N23 in Velenjak.

As shown in the table, the selected neighbourhoods in Tajrish have 12 digits in common relating to A-B-C while only the last 4 digits relating to their neighbourhood IDs are different. In the same way, the FNIDs of the neighbourhoods in Velenjak have similar 12 digits and only their last 4 digits are unique (table 7.4). This indicates the uniqueness of each FNID, and also the degree of homogeneity/heterogeneity of the patterns at different scale levels. For instance, the last four digits of the neighbourhoods T-N1, T-N11, and T-N15 are similar, and therefore, homogeneous. The last 8 digits of FNIDs relating to local and neighbourhood levels of Tajrish and Velenjak (compare table 7.3 with 7.4) are notably different, indicating that the patterns of these two areas are heterogeneous.

In short, three main advantages can be outlined for FNID. Firstly, FNID suggests that the degree of homogeneity and heterogeneity of urban patterns can be measured mathematically. It can be used as a controlling tool to direct urban new developments and interventions to be built within certain ranges of fractal dimensions. This could provide an effective way to conserve urban qualities by a more accurate and at the same time more flexible method than the current type of tight restriction.

Secondly, FNID suggests an accurate method for patterns recognition. The method proposed here assists transfer of the geometric shapes to the numerical codes extracted from the existing urban patterns. Therefore, FNID can be defined as a mathematical signature that recognises more accurately the differences in physical complexity of different neighbourhoods. Thirdly, it can be suggested that FNID is a more abstract, but accurate, way to identify urban patterns, as compared to fractal maps, because it provides an exclusive pattern identification code for every neighbourhood of the city – it is also arguably unique worldwide. Finally, the similarity and dissimilarity between each section of 4-space FNIDs are an indication of homogeneity and heterogeneity of the patterns at different city scales. While such similarities can be used to group similar patterns under one category or class, a fractal map is an easier tool – as compared to an FNID – to seek groupings of similar patterns or pattern classification, which is the subject of the next section.

7.2 Part Two: Fractal classification of urban patterns

7.2.1 Advantages of fractal classification

From a simple description of planned/unplanned patterns (e.g. as given by Kostof, 1991) to more detailed descriptions (e.g. as given by Lynch, 1981), some urban morphologists have sought to suggest different ways of classifying urban forms and patterns. However, even the detailed classifications have sometimes been associated with ambiguity when interpreting and categorising some patterns. Marshall (2005) noticed this problem and stated that, in some cases, the same form could be described by different labels. Conversely, a particular label may have different structural connotations, and therefore, it might be used to describe quite different patterns in different contexts. Marshall (2005, p.75) concludes that recognition and representation of urban patterns are perhaps 'in the eye of the beholder'.

While each method of pattern classification might have its own advantages, one of the advantages of the fractal classification of urban patterns is that it can provide a mathematical gauge for classifying urban patterns based on the degree of complexity that their shapes demonstrate. In this sense, urban patterns can be classified independently of the eye of the examiner by assessing their fractal dimension and illustrating their complexity in terms of fractal maps. The other advantage of fractal classification is that it could assist urban planners and particularly urban conservationists in identifying more accurately the boundaries where planning restrictions might be applied to maintain the urban physical characteristics of the designated areas.

The complexity of urban form is always a matter of degree. The fractal map produced in the previous chapter (figure 6.11) suggests a classification method by dividing the range of assessed fractal dimensions (1.1000 to 1.8999) into eight classes, indicating the degree of morphological complexity that each part poses. The number of classes can be adjusted according to the purpose of examination by changing the number breakpoints while dividing the range of fractal dimensions. Eight classes introduced in Chapter Six was an introductory example – maximising the number of classes by decreasing the range of fractal dimensions in each class. However, in this chapter, the assessed fractal dimensions are divided into three ranges – a) lower than 1.4000, b) between 1.4000 and 1.6999, and c) above 1.6999 – to facilitate pattern recognition. In this way, the urban patterns can be classified as low, medium, and high complexity respectively. The pictorial version of these ranges has been illustrated in figures 7.5, 7.6, and 7.7.

The initial comment on these figures is that the classified patterns cannot be separated with precise linear boundaries. Since each class has some overlaps with the others, they can only be separated by fuzzy boundaries. These figures also show clearly the dispersion of each class. For instance, figure 7.5 illustrates how the patterns with high degree of complexity distributed over the district of Shemiran (e.g. the urban patterns around A1, and A10, Tajrish, Darakeh, the two old centres in Shemiran).

More importantly, the overlaps between two classes indicate the area that an urban pattern begins distortion. Figure 7.8 highlights the areas that the patterns with high and medium degree of complexity begin to distort (highlighted with yellow colour). The overlaps between the first and the third class indicate the critical areas (highlighted with red colour). Further comments are elaborated for each class separately in the following sections.

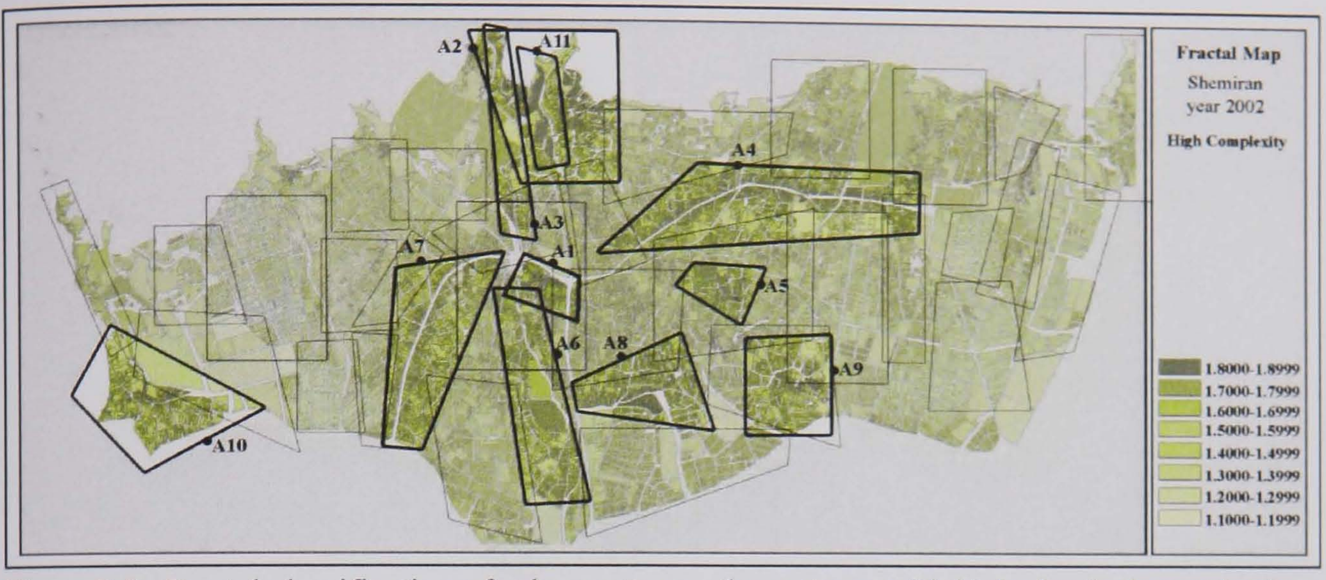


Figure 7.5: Fractal classification of urban patterns; the patterns with high physical complexity (fractal dimensions above 1.6999) have been highlighted.

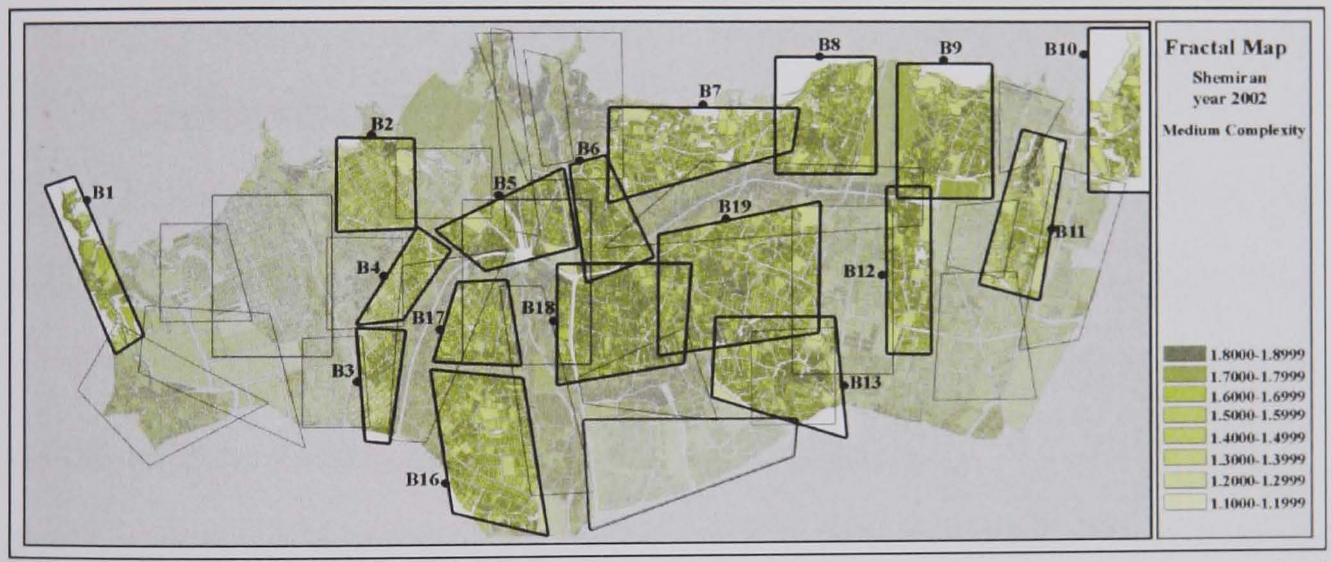


Figure 7.6: Fractal classification of urban patterns; the patterns with medium physical complexity (fractal dimensions between 1.4000 and 1.6999) have been highlighted.

Figure 7.7: Fractal classification of urban patterns; the patterns with low physical complexity (fractal dimensions below 1.4000) have been highlighted.

Figure 7.8: The areas which their patterns begin to be distorted are highlighted in yellow, and the areas with highly critical status are marked in red.

7.2.1.1 Urban patterns with high complexity:

Figure 7.5 exemplifies the areas of the case study in which the urban patterns have a high degree of physical complexity. The shapes of the patterns in these areas (labelled from A1 to A11) are mostly curvilinear, resulting from gradual organic development of their neighbourhoods. Some contain radial branching shapes with one or two urban local centres such as A9, A10 (figure 7.9, below), and A5,; some have linear tree-like shapes such as A3, A4, A6, A7, and A11, with no specific centre (figure ?7.10), and some are composed of a mixture such as A1, A2 (Figure 7.9, above) and A8.

The examples given in figure 7.9 had all been small villages – like Tajrish – that evolved gradually over a long period before being engulfed in the metropolitan spread of Tehran. It seems that their physical complexity has persisted up to the present except for those parts which have recently experienced rapid changes (the analysis of such changes will be discussed later in this chapter). This also suggests that the areas around the centre of old neighbourhoods have generally high fractal dimensions. In other words, the older is more complex.

Figure 7.9: Some examples of the old and organically grown urban patterns with high physical complexity. Tajrish Bazaar (A1), Darband (A2), Chizar (A9), and Darakeh (A10).

Figure 7.10 shows some of the patterns with high physical complexity which have linear tree-like branching shapes. For the cases of A3, A6 and A11 (figure 7.5, and figure 7.10) the reason for having high complexity can be interpreted as their gradual development along a natural geographical element (the seasonal canal) over centuries (e.g. A6). In the case of A4, the complex urban patterns developed along an old route (Niavaran Street) connecting Tajrish to the Niavaran Palace (figure 7.10). The only planned road in this area which demonstrates high spatial complexity on both sides is Vali-Asr Street (figure

7.10, A7). The street was ordered by Reza Shah (the first king of the Pahlavi period) to connect the south of Tehran to the north (Tajrish) in 1928 (Sotoudeh, 1995).

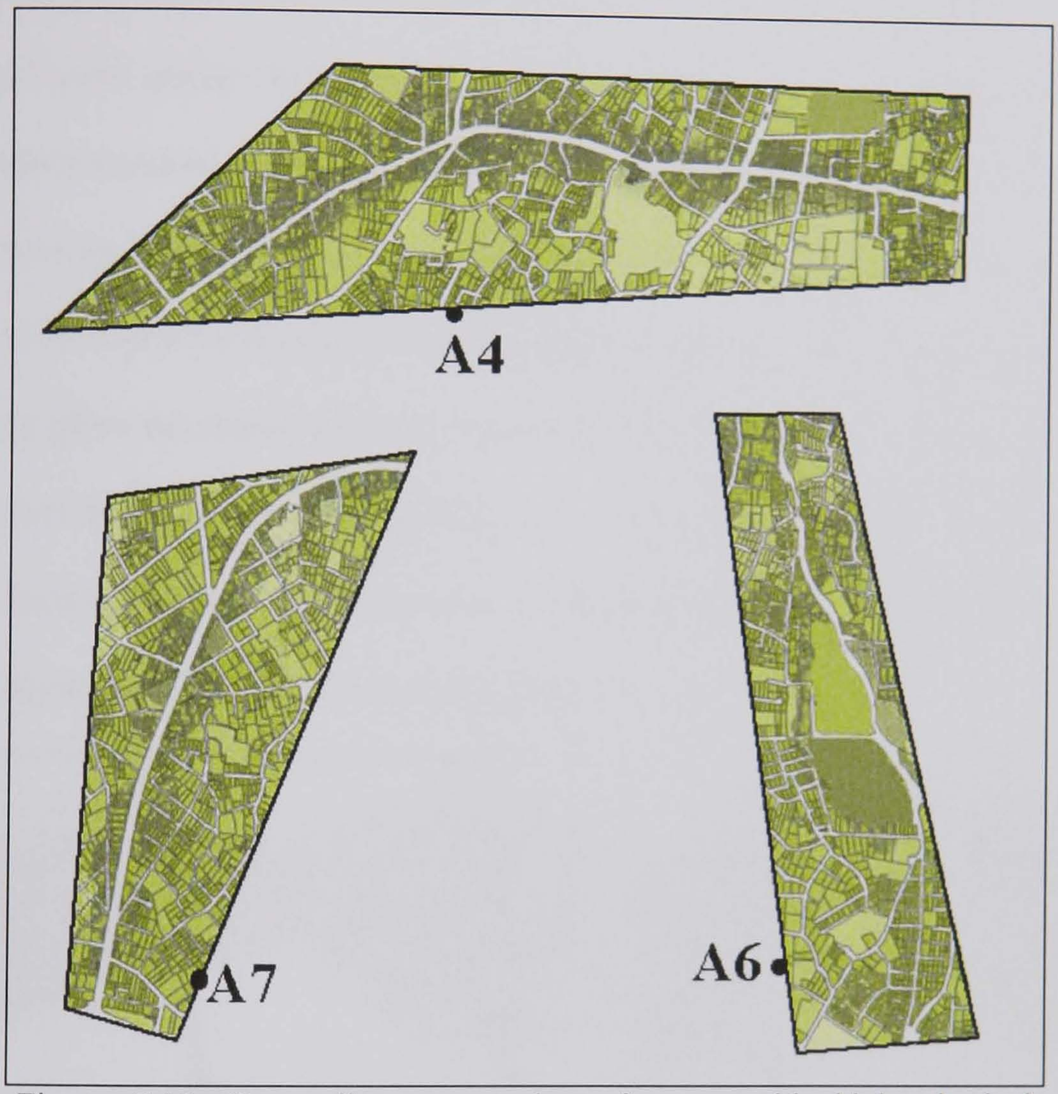


Figure 7.10: Some linear examples of areas with high physical complexity (Fb>1.6999). The gradually evolved pattern alongside the natural seasonal canal (A6) and the fractal patterns along historical routes (A7, Vali-e Asr Street, and A4, Niavaran Street).

An important common characteristic of A4 and A7 is that they have both been substantially regenerated during the last two decades and new buildings with very diverse developments and building types replaced the old ones. It seems that the main reason that the high physical complexity has been maintained along these routes is the impact of the old tall trees planted on both sides of the streets (see also figure 7.25 and Appendix D). This clearly indicates the role of trees in maintaining physical complexity of these areas.

7.2.1.2 Urban patterns with medium complexity:

As explained in Chapter Five, the original urban patterns in Shemiran followed a traditional Iranian garden layout with comparatively large plot sizes. The new modern type gradually replaced the traditional types (see figures 5.13 and 5.14) with rather smaller plot sizes when the city of Tehran expanded towards its suburban villages. The reason for this is obviously related to the significant increase in the land price, which encouraged urban developers to divide them into smaller plots with new boundaries to build up more dense and modern residential neighbourhoods (Sotoudeh, 1995). The result of such a transformation is the emergence of a typology consisting of modern buildings in pure rectangular plots surrounded by an organic street layout.

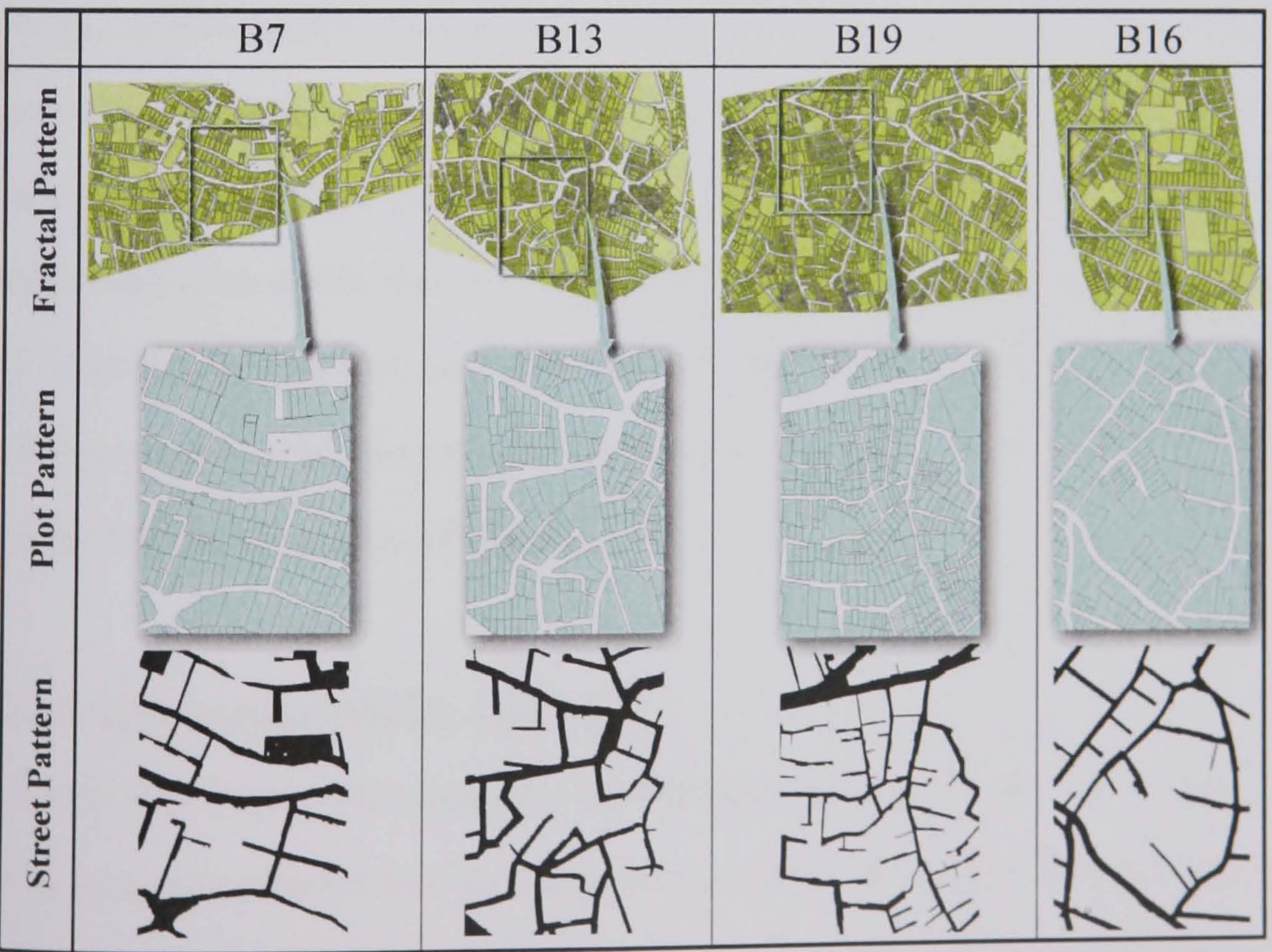


Figure 7.11: Some examples of urban patterns with medium complexity (1.4000>Fb>1.6999). This class is mainly observed in an urban neighbourhood typology that consists of the rectangular plot patterns embodied in their organic street patterns.

The majority of the neighbourhood patterns marked in figure 7.6 as medium complexity consists of such a typology. They have inherited their main structure and their street patterns (figure 7.11, bottom) from the past with seemingly irregular shapes resulting from their organic and gradual evolution. However, apart from the street patterns, their neighbourhoods' plot layouts have been mainly regenerated at architectural scales and each of the large plot sizes divided to form smaller plots with pure\rectangular shapes (figure 7.11, middle). The fractal dimensions of these neighbourhoods are mainly between 1.4000 and 1.6999 and, therefore, they can be classified as patterns with medium physical complexity (figure 7.11, above).

Larkham (1996b) explains the logic behind the emergence of such a typology through Conzen's (1962) concept of Longevity. According to this concept, change tends to occur faster on smaller scales. He explains that as properties are bought and sold through the years, buildings decay and change more rapidly than plots, and plot size and pattern may change much more rapidly than the street pattern. Therefore, in terms of longevity, 'there is a hierarchy of streets, plots, and buildings in that order' (Larkham, 1996b, p.32). He also argues that even in a modern urban landscape, where change on large scales occurs quickly, Conzen's concept is still applicable.

7.2.1.3 Urban patterns with low complexity:

The areas with low physical complexity are highlighted in figure 7.7 (C1, C2..., C12). These areas have generally been developed within the last four decades (after the first master plan of Tehran in 1968) and they have mostly planned urban layouts where regular Euclidian geometry dominates. The majority are the residential areas, which have been developed during the fast expansion of Tehran towards its suburbs and are less than 40 years old. Their streets have gridiron patterns with a defined hierarchy connecting them to the main structure of the city.

The residential neighbourhoods of Shemiran with low complexity are either totally designed including the blocks, plots and their constituent buildings (e.g. C1, C3, C9), or partly designed – excluding their buildings (e.g. C4, C6, C8, and C12). Although the latter group have slightly higher fractal dimensions, all can be classified fractally in the category of low complexity (figure 7.12).

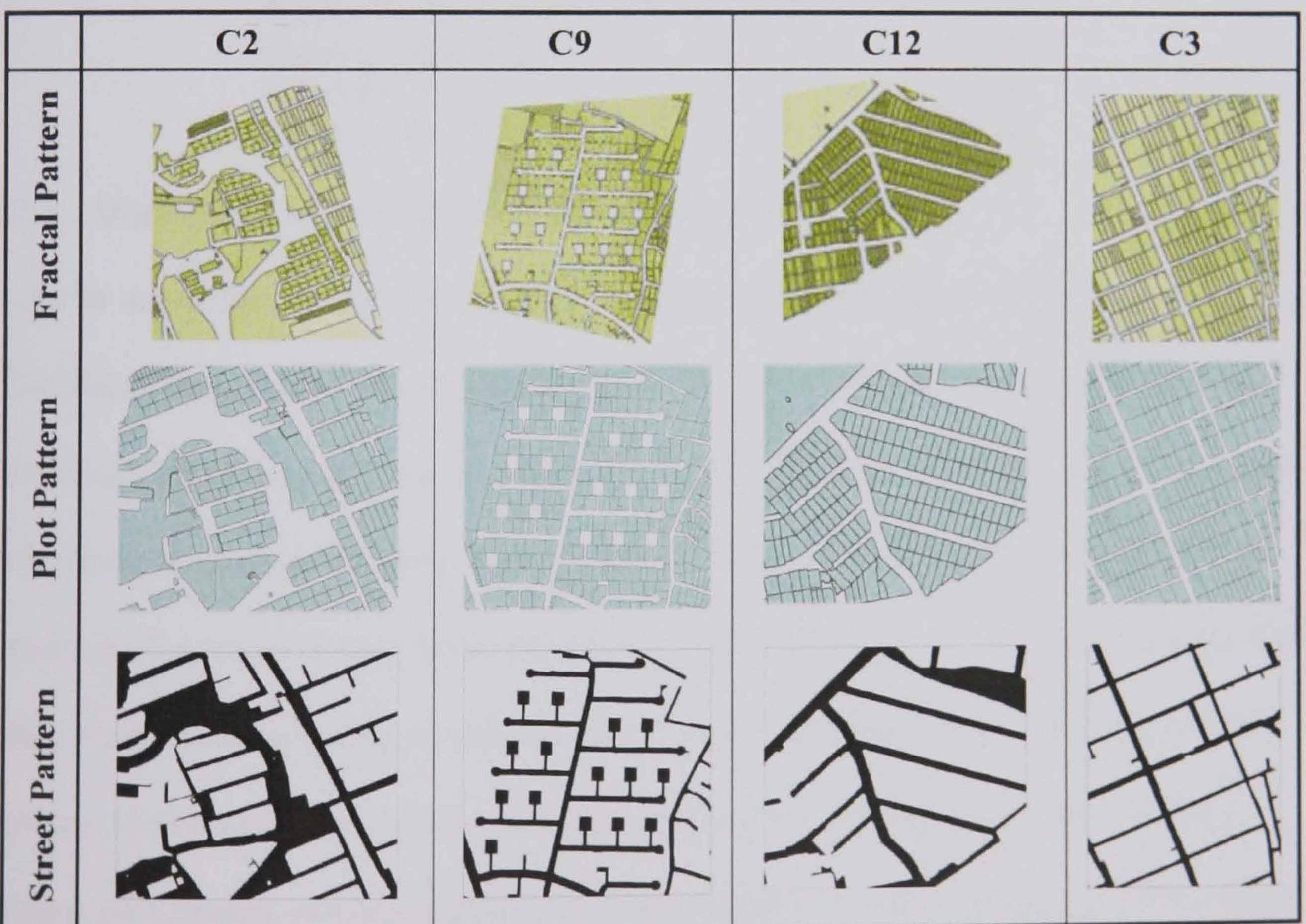


Figure 7.12: Some examples of urban patterns with low complexity (Fb<1.4000) and the rectangular plot patterns embodied in their planned street patterns.

In addition to the new residential developments, the areas marked C1-a, C1-b, and C1-c (figure 7.13) are relatively large plots where the site layout and buildings were designed in pure Euclidian shapes for particular events or purposes (university campus, meeting hall, exhibition). The fractal dimensions assessed for these parts are 1.1812, 1.0731, and 1.1240 respectively, which reveals that they also have very low physical complexity.

Figure 7.13: Examples of designed areas with low physical complexity, the University of "Shahid Beheshti" (C1-a), "Ejlas-e Saran" Meeting Hall (C1-b), and the site of International Exhibition of Tehran (C1-c).

7.2.2 Discussions of Fractal classification of urban patterns:

It can be noted that in some cases where street patterns are geometrically regular (Euclidian), their fractal assessments might indicate a medium complexity, while a low complexity could be expected (e.g. B2). This might result from the degree of complexity demonstrated by other constituent parts of those areas rather than the structure of their streets. As the research uses aerial photos as its prime data source, the composition of all urban elements constituting an urban pattern (plots, buildings, trees, etc) is taken into account. However, it is possible to test the complexity of each urban element (block pattern, plot pattern, building pattern, etc) individually. For this, an element type should be selected (e.g. streets) and other urban elements removed from the aerial photos before fractal examination. Alternatively, other sources of data can be used – as input data – in which an urban element is solely represented (e.g. a street map in the case of assessing a street pattern).

In the examples given in figure 7.11, similar street patterns demonstrated similar degrees of physical complexity. However, there are also areas with similar street patterns whose fractal patterns express different degrees of complexity (e.g. A5, B19, C2), or areas with similar complexity might have different street patterns (e.g. B2, B16). This indicates that classification of the street patterns does not necessarily conform to the fractal classification of urban patterns. For instance, the street patterns of areas C2 and A5 can both be classified as curvilinear (see Marshall, 2005), while they are fractally classified under different categories. From a morphological point of view, the main difference between C2 and A5 is that the first has been created by design while the second one is the outcome of a gradual (organic) growth. In other words, fractal classification might better address the nature of urban growth, change and pattern evolution than other classification methods. This issue will be elaborated in the next part of this chapter.

7.3 Part Three: Measuring the change in urban patterns

7.3.1 Change analysis of the urban patterns of Tajrish from 1956 to 2002

At the case study examination stage (Chapter Six), fractal dimensions of 24 neighbourhoods in Tajrish were assessed for the year 2002. The same method was employed to measure fractal dimensions of these neighbourhoods in the past by using aerial photos of Tajrish for the years 1956, 1969, and 1979. The result of the fractal assessment for these years can then be compared with a more recent time (in the year 2002) to measure accurately the degree of change occurring at the local scale (Table 7.5) and at the neighbourhood scale (Table 7.6).

The Assessment years	1956	1969	1979	2002
Fractal dimension	1.7583	1.8631	1.8570	1.8047

Table 7.5: The fractal dimensions of the urban patterns at local scale of Tajrish for the years 1956, 1969, 1979, and 2002 (the area size of 1200metre×800metre squares).

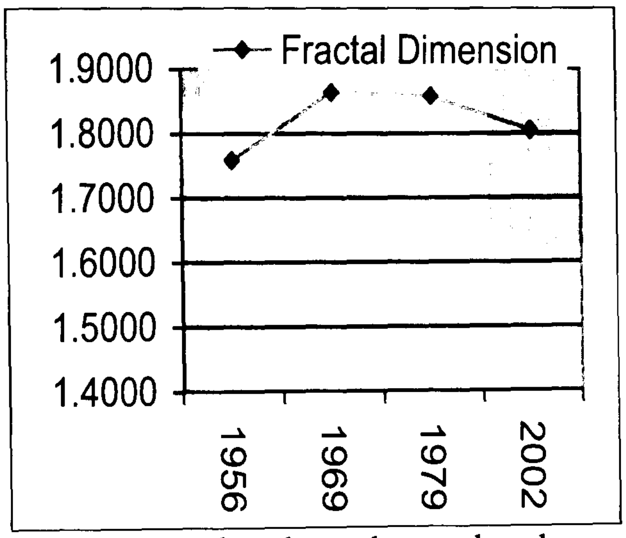


Figure 7.14: the chart shows the change in physical complexity of Tajrish at local scale from 1956 to 2002.

According to figure 7.14, and table 7.5, fractal dimension assessment can explain the degree of changes occurring in the physical complexity of the urban pattern of Tajrish from 1956 to 2002. The aerial photos show that some of the large plots and vacant sites were built upon between 1956 and 1969 and the amount of green space also increased (figure 7.15, for a larger version of the aerial photos see appendix E). These two reasons are enough to increase the complexity of urban patterns in Tajrish in 1969. The line of the fractal dimension change (figure 7.14) also indicates the degree of physical complexity was sustained between 1969 and 1979, while some large-scale urban interventions and the newly imposed modernist pattern can account for the decreasing complexity in 2002. Table 7.5 is based on the fractal assessment of the area size of 1200x800 square meters. However, if that area is split into sub-areas of 200x200 square meters, the change can be assessed for each individual neighbourhood (table 7.6).

Neighbourhoods' ID	Fb-1956	Fb-1969	Fb-1979	Fb-2002
Tajriah-N1	1.5702	1.7781	1.7570	1.8502
Tajriah-N2	1.4326	1.7394	1.6998	1.7239
Tajriah-N3	1.6520	1.7760	1.7714	1.7458
Tajriah-N4	1.7732	1.8779	1.7128	1.7898
Tajriah-N5	1.7452	1.8254	1.6391	1.7329
Tajriah-N6	1.4342	1.4354	1.6182	1.7016
Tajriah-N7	1.5780	1.7362	1.6939	1.7460
Tajriah-N8	1.6125	1.7073	1.7197	1.7554
Tajriah-N9	1.7901	1.7949	1.6743	1.7758
Tajriah-N10	1.6321	1.6967	1.6892	1.5366
Tajriah-N11	1.8079	1.7984	1.8161	1.7106
Tajriah-N12	1.5956	1.7672	1.6656	1.6346
Tajriah-N13	1.7317	1.7536	1.6982	1.7593
Tajriah-N14	1.6625	1.8005	1.7713	1.7808
Tajriah-N15	1.7432	1.8168	1.8084	1.7882
Tajriah-N16	1.6640	1.7585	1.7785	1.7846
Tajriah-N17	1.7249	1.7685	1.6764	1.7500
Tajriah-N18	1.7621	1.8547	1.7955	1.7849
Tajriah-N19	1.7513	1.8418	1.7669	1.7567
Tajriah-N20	1.7659	1.8428	1.7981	1.7751
Tajriah-N21	1.7156	1.7599	1.8536	1.7768
Tajriah-N22	1.7756	1.8381	1.7510	1.7141
Tajriah-N23	1.7926	1.8256	1.7259	1.7388
Tajriah-N24	1.8120	1.8334	1.7393	1.6996

Table 7.6: The fractal dimensions of 24 neighbourhoods in Tajrish for the years 1956, 1969, 1979, and 2002.

The procedure explained in the previous chapter can be carried out to convert the numerical data of table 7.6 to pictorial data of figure 7.15. The fractal palettes illustrated in figure 7.15 have been compared to measure the changes occurring in each of the neighbourhood units in Tajrish from 1956 to 2002. While the numerical data provide an accurate mathematical comparison, the pictorial data provide a visual comparison capturing the decrease or increase in physical complexity of each neighbourhood.

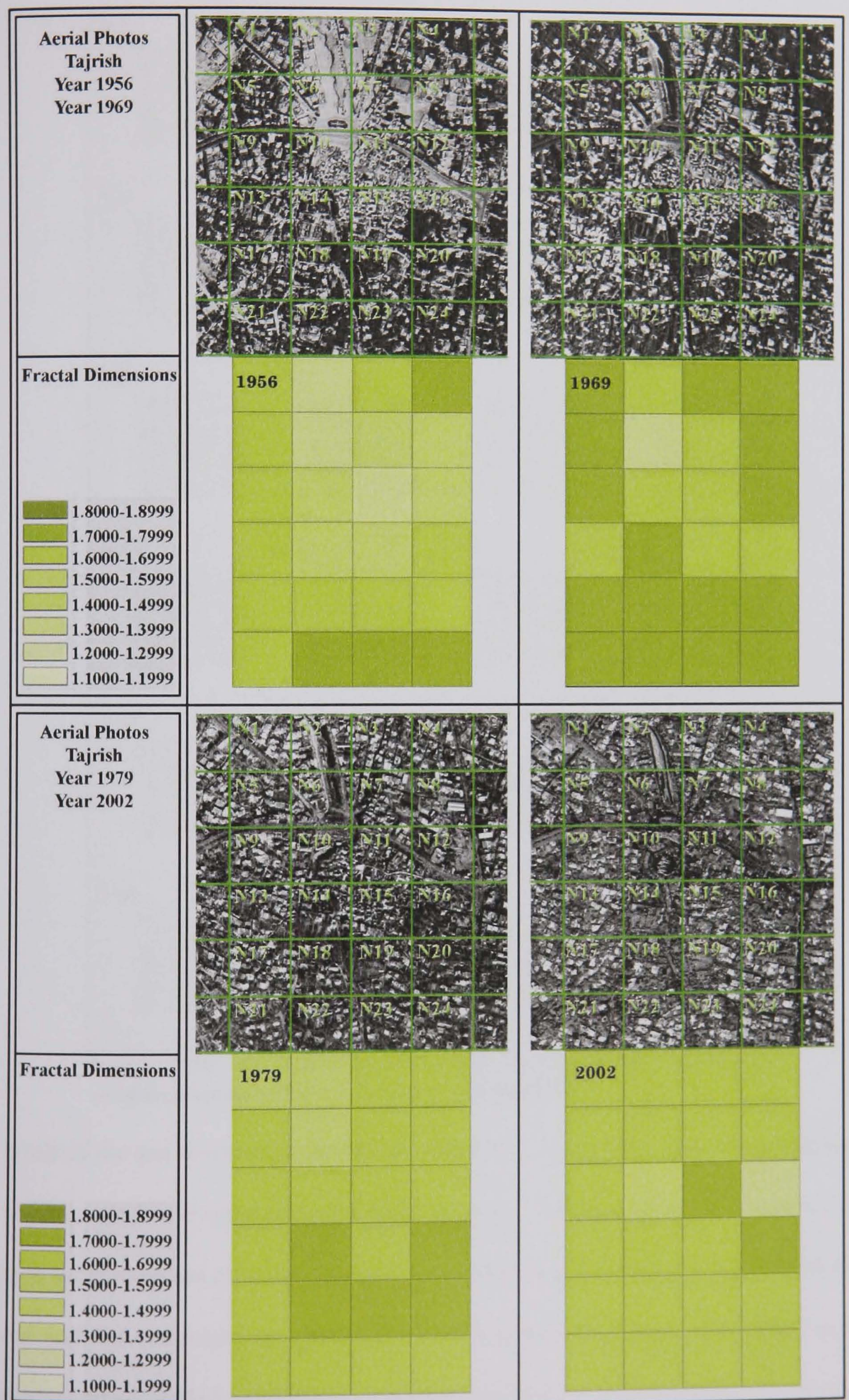


Figure 7.15: Fractal Dimensions of 24 neighbourhood units of Tajrish for the years 1956, 1969, 1979, and 2002 (each unit is equal to 200metre×200metre squares).

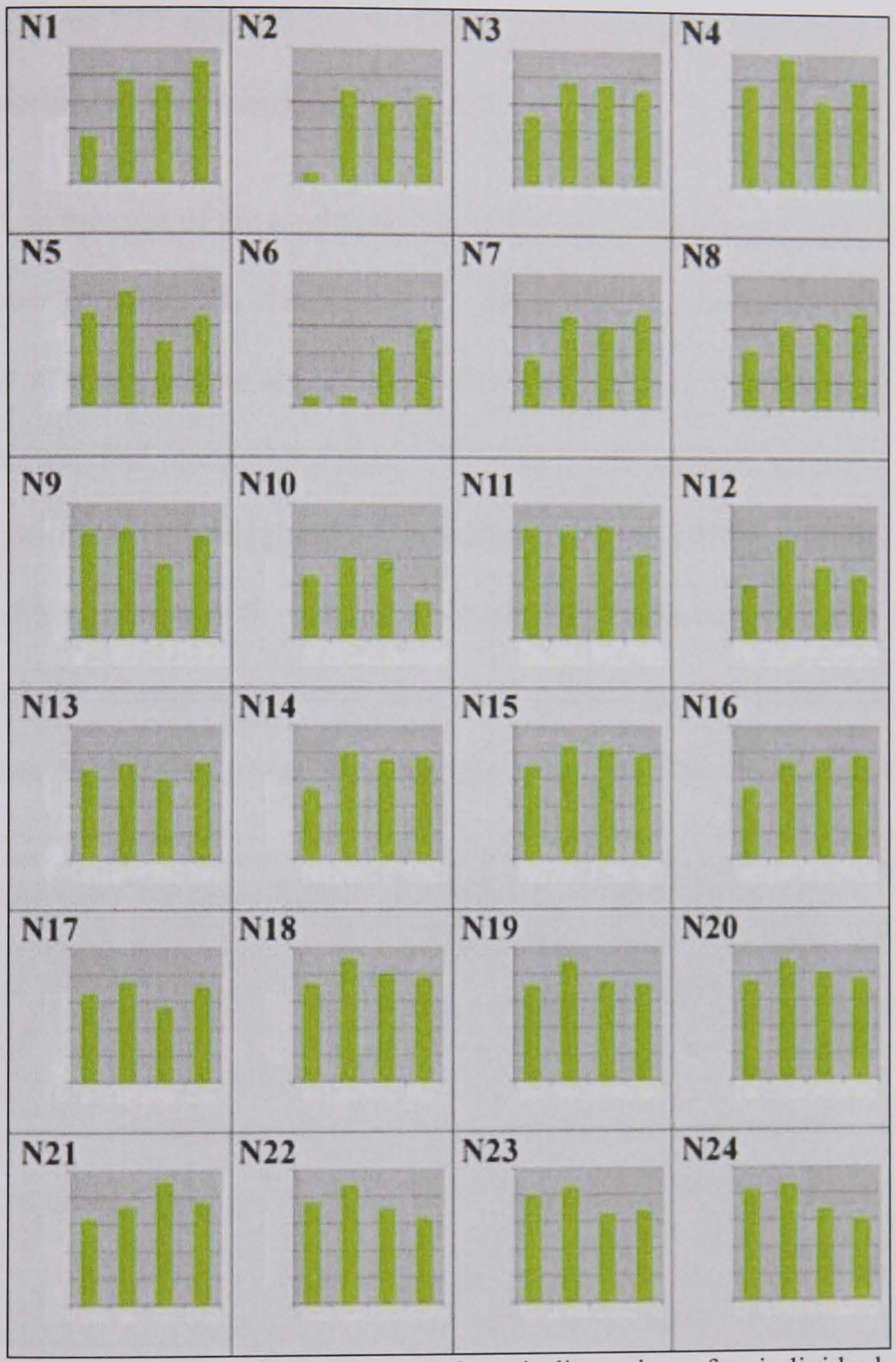


Figure 7.16: the fluctuation of fractal dimensions for individual neighbourhoods of Tajrish between 1956 and 2002.

The result of the test reveals that the fractal dimension method as a spatial assessment tool is very sensitive to urban morphological change. The column charts in Figure 7.16 illustrate the fluctuation of fractal dimension for each neighbourhood from 1956 to 2002. The rise and fall in fractal dimensions of the neighbourhoods depend on the degree of changes occurring in their constituent components. Some of these changes have been analysed in figures 7.17 and 7.18 and the fractal analysis charts of the other neighbourhoods have been added in appendix F.

As expected, in the case of the neighbourhoods that have experienced significant physical transformations (e.g. N1, N2, N3, N10, N12), their respective fractal dimensions have changed. For instance, a large area in neighbourhood N10 was demolished in 1997 to become a bus terminal (marked in figure 7.17). The fractal analysis indicates that the spatial complexity of N10 fell significantly between the years 1979 and 2002. However, in the case of N1, two major rises can be detected. The first is between 1956 and 1969 when the majority of empty plots were developed and occupied with buildings, and the second is from 1979 to 2002 when the amount of vegetation increased (figure 7.17).

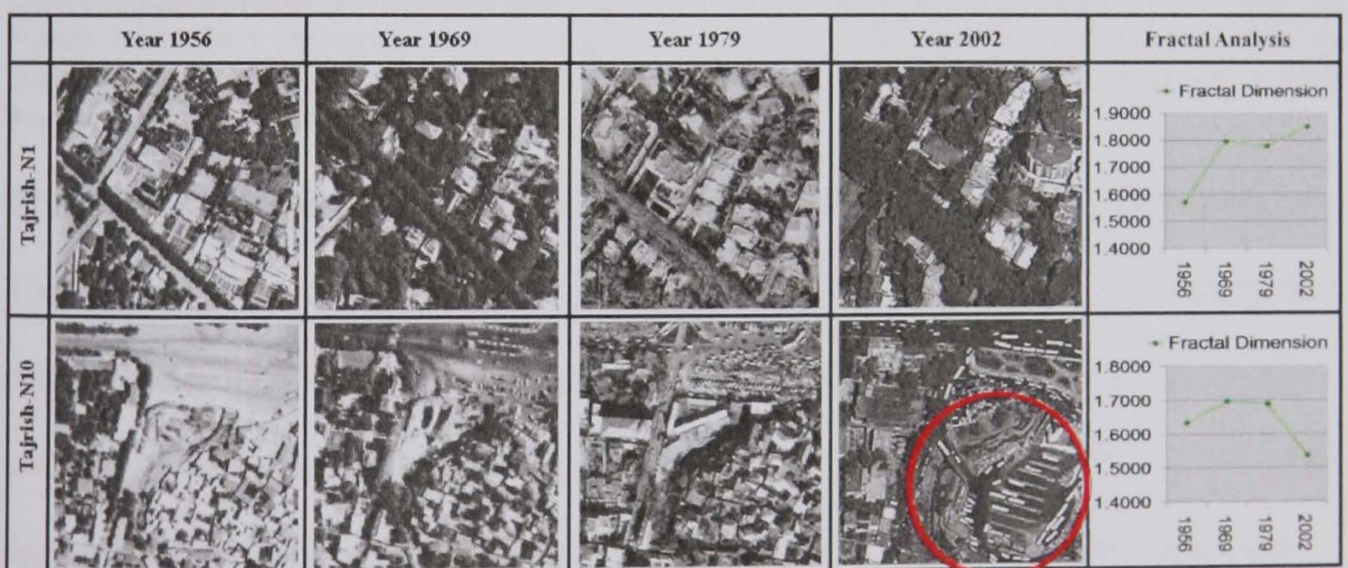


Figure 7.17: Two examples of the neighbourhoods in Tajrish that have been undergone considerable changes in their patterns as reflected in their assessed fractal dimensions (the right-hand line charts). The large-scale change occurring in N10 has been marked with a red circle.

Conversely, in those areas whose morphological components have changed relatively little, their respective fractal dimensions indicate less fluctuation over time. For instance, the low level of change to the constituent urban elements of neighbourhood N15 has led to its fractal dimension remaining more or less constant (figure 7.18). Neighbourhoods N11, N13, N16, N22, and N24 are similar to N15 in this sense. For instance, in the case of N11, the physical complexity has been sustained for the years of 1956, 1969, and 1979. However, in that particular neighbourhood, the decrease between 1979 and 2002 can be interpreted as the result of the addition of the modern shopping mall – "Bazaar-che Ghaem" – alongside the linear traditional bazaar (marked with a red circle in figure 7.18).

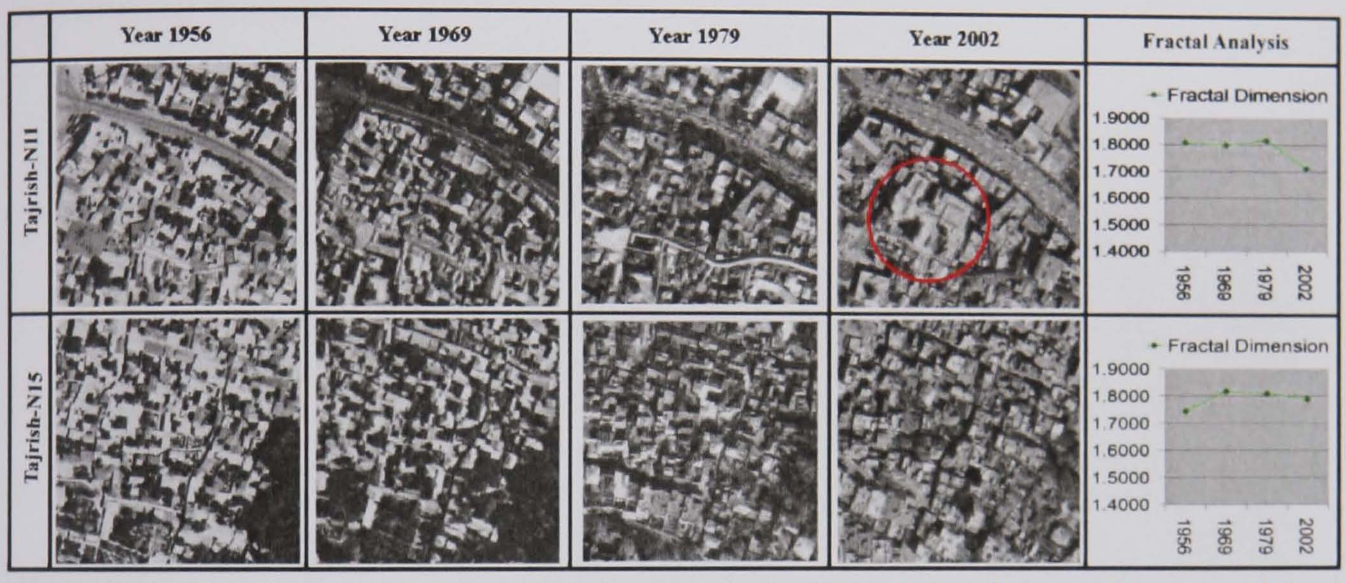


Figure 7.18: Two examples of the neighbourhoods in Tajrish that have undergone minimal change in their urban patterns as reflected in the fractal diagrams too. The only notable change has occurred in N11 (marked with a red circle) in 2002.

7.3.2 Change analysis through the "add and remove" technique (A-R-Technique)

The 'add and remove' is a simple technique for measuring the potential future changes caused by urban policies or design proposals. This technique assists decision makers in testing how their decisions will change urban spatial complexity, and to choose the urban scenario which may better adapt to an existing urban pattern. Two examples are given below in terms of "proposal testing" and "policy testing" to show how this technique can be applied.

7.3.2.1 <u>Proposal testing</u>:

Both architectural projects and urban design interventions may maintain or change the physical complexity of an existing urban context depending on whether their proposed forms demonstrate the same degree of complexity as already exists. In section 7.3.1, it was discussed how some urban projects changed dramatically the complexity of two neighbourhoods in Tajrish (the implementation of the bus terminal and the large shopping mall in N10 and N11 respectively, figures 7.17 and 7.18). This research suggests that the morphological impacts of new urban proposals should be tested in laboratory before they are implemented in reality.

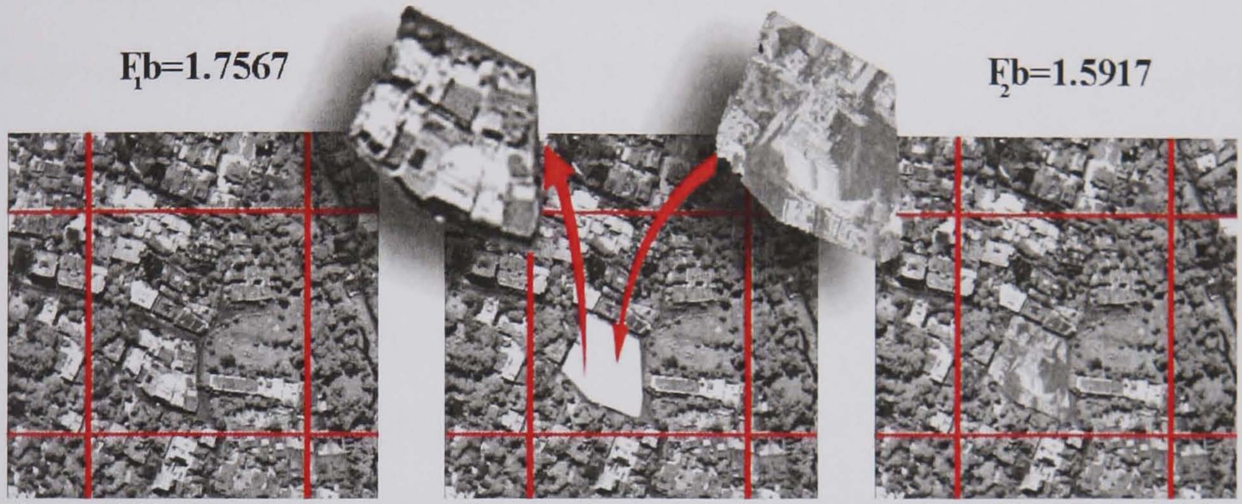


Figure 7.19: fractal assessment of a hypothetical design proposal for N19 in Tajrish. The fractal dimension of its neighbourhood pattern has been reassessed by replacing an existing urban form (left) with the proposed one (right).

Assume that a developer suggests a high-rise building to be built as a replacement for the existing buildings in Tajrish-N19. The A-R-Technique can be used for reassessment of fractal dimension by removing the existing buildings and adding the site plan of that hypothetical project as shown in figure 7.19. In the case of that hypothetical proposal, the fractal dimension of the neighbourhood pattern in N19 decreases from 1.7567 to 1.5917 (a 16.5% complexity reduction at the neighbourhood scale). If the impact of such a proposal is examined at a local scale (table 7.7), the change will be only 1.5% – dropping from 1.8047 to 1.7903. In the first instance, this small change has little impact at the district and city scales – FNID of N19 is changed from 7567-8047-7562-6918 to 5917-7903-7561-6918. However, according to the butterfly effect (discussed in Chapter Three), even this 1.5% change at the local scale may turn into big changes at the city scale – taking into account the number of incremental changes and their consequences when they accumulate over 5 or 10 years time. Therefore, this 1.5% change at local scale (or 16.5% change at the neighbourhood scale) must be treated with extreme caution.

The Scale of Assessment	Neighbourhood scale (Tajrish-N19)		Local Scale (Tajrish)	
	Fb	*F'b*	*Fb*	*F'b*
Fractal Dimensions	1.7567	1.5917	1.8047	1.7903

Table 7.7: The degree of changes in physical complexity of Tajrish-N19 imposed by a hypothetical proposal at neighbourhood and local urban scales.

It would be possible for urban specialists or conservationists to use the existing FNIDs as benchmarks and to define an acceptable range of fractal dimensions for each part of the city at different scales (e.g. between the minimum and maximum of their FNIDs) in order to control the degree of urban morphological changes caused by urban interventions and to conserve neighbourhoods' identity in terms of its physical complexity. Accordingly, architectural or urban design proposals that are not within this range can be rejected. Nevertheless, in some cases, a kind of modern urban structure, or an avant-garde building, might be proposed to be built in an old urban fabric as an urban surprise (e.g. a landmark); this can be passed to urban specialists in a higher level of planning authority to allow such degree of change for that particular context or not.

As the focus of the research is examining the change in complexity of urban patterns, the fractal analysis has been limited to the analysis of the patterns through aerial photos. However, for a comprehensive change analysis, other urban morphological features should also be taken into account, such as change in street elevations, street vistas, urban skylines, network pattern, landmark distribution, etc. For instance, the A-R-Technique can be employed to measure the change in urban skylines of T-N19, by redrawing the skylines based on the elevation of the proposed design and then reassessing its fractal dimension using the "ruler method" (explained in Chapter Three, section 3.3.5.2).

7.3.2.2 Policy Testing:

Some urban policies might have direct or indirect impacts on urban forms and patterns. The degree of changes that these policies may impose on urban morphological features – particularly on the complexity of neighbourhood patterns – can be measured. As an example, one of the important and influential road regenerating policies of Tehran's master plan is the *'Tarh-e Taariz'* (the street widening policy).

Street widening has a long history both in Iran and worldwide (e.g. Haussmannised Paris and Reza Pahlavi's ideas for Tehran; see Chapter Five, section 5.1.1.3). The concept was also used in wide variety of "technocentric plans" proposed for British towns and cities during and immediately after the Second World War (Diefendorf, 1989; Larkham, 1997). However, the complex process of preparing, approving and implementing a street widening plan introduced conflict, confusion and delay in some cases even when a high-profile expert was commissioned to produce it (see Larkham, 2009). Particularly, in the context of old British cities and towns, the street widening policy was eventually discarded in the favour of a new culture of conservation by the 1960s. In the case of Tehran, however, this policy is still in practice.

According to the recent master plan of Tajrish, many existing streets should be widened and straightened. Its goal was to facilitate traffic movement and to improve accessibility in the case of emergencies (with the minimum width allowance of six metres). This plan was initially prepared in 1992, and revised once in 2002 (see ACAUP, 2002; Municipality of Tehran, 2003). Planners identified many narrow alleys, cul-de-sacs, and old streets to be widened between 1 to 20 metres over a period of 25 years. The future physical consequences of such a policy at the neighbourhood level of the research case study can be analysed by the A-R-Technique and fractal analysis method as explained below.

Figure 7.20 illustrates the oldest part of Tajrish that streets have to be widened, extended, or straightened according to the new street layout. As the map shows, the new layout cut through some blocks trimming many building edges, which will considerably change the urban pattern of Tajrish in future. If the Municipality of Tehran can afford the cost, the marked areas will be gradually regenerated according to this layout. Otherwise, each building edge has to step back its owner applies for planning permission to whenever rebuild or renovate his property.

Figure 7.20: The street widening plan around Tajrish Square. The map in the background is the existing situation (year 2002) and the map on the top left shows the new street layout. (Municipality of Tehran, 2003, unpaginated)

The aim of the master plan of Tajrish is that the street widening plan will be gradually implemented and completed by the year 2017. The 2002 aerial photo of Tajrish can be amended by adjusting the streets to show their proposed dimensions (length and width), and then the method explained earlier can be used to measure the change in the fractal dimension of its new status (table 7.8 and figure 7.21). In this test, changes that may occur in other urban elements have been ignored in order to discover the degree of physical change caused by this one policy alone.

Neighbourhood ID	T-N1	T-N2	T-N3	T-N4	T-N5	T-N6	T-N7	T-N8
Fb for the year 2002	**1.8502**	**1.7239**	**1.7458**	**1.7898**	**1.7329**	**1.7016**	**1.7460**	**1.7554**
Fb for the year 2017	1.6630	1.5732	1.5530	1.6287	1.5943	1.6430	1.5228	1.6059
Neighbourhood ID	**T-N9**	**T-N10**	**T-N11**	**T-N12**	**T-N13**	**T-N14**	**T-N15**	**T-N16**
Fb for the year 2002	**1.7758**	**1.5366**	**1.7106**	**1.6346**	**1.7593**	**1.7808**	**1.7882**	**1.7846**
Fb for the year 2017	1.6437	1.5034	1.5905	1.5558	1.6101	1.6097	1.5911	1.5443
Neighbourhood ID	**T-N17**	**T-N18**	**T-N19**	**T-N20**	**T-N21**	**T-N22**	**T-N23**	**T-N24**
Fb for the year 2002	**1.7500**	**1.7849**	**1.7567**	**1.7751**	**1.7768**	**1.7141**	**1.7388**	**1.6996**
Fb for the year 2017	1.6074	1.6134	1.5702	1.5791	1.5808	1.5617	1.6035	1.5749

Table 7.8: The degree of change in fractal dimensions of the neighbourhoods in Tajrish if the street widening policy is implemented and completed (e.g. by 2017).

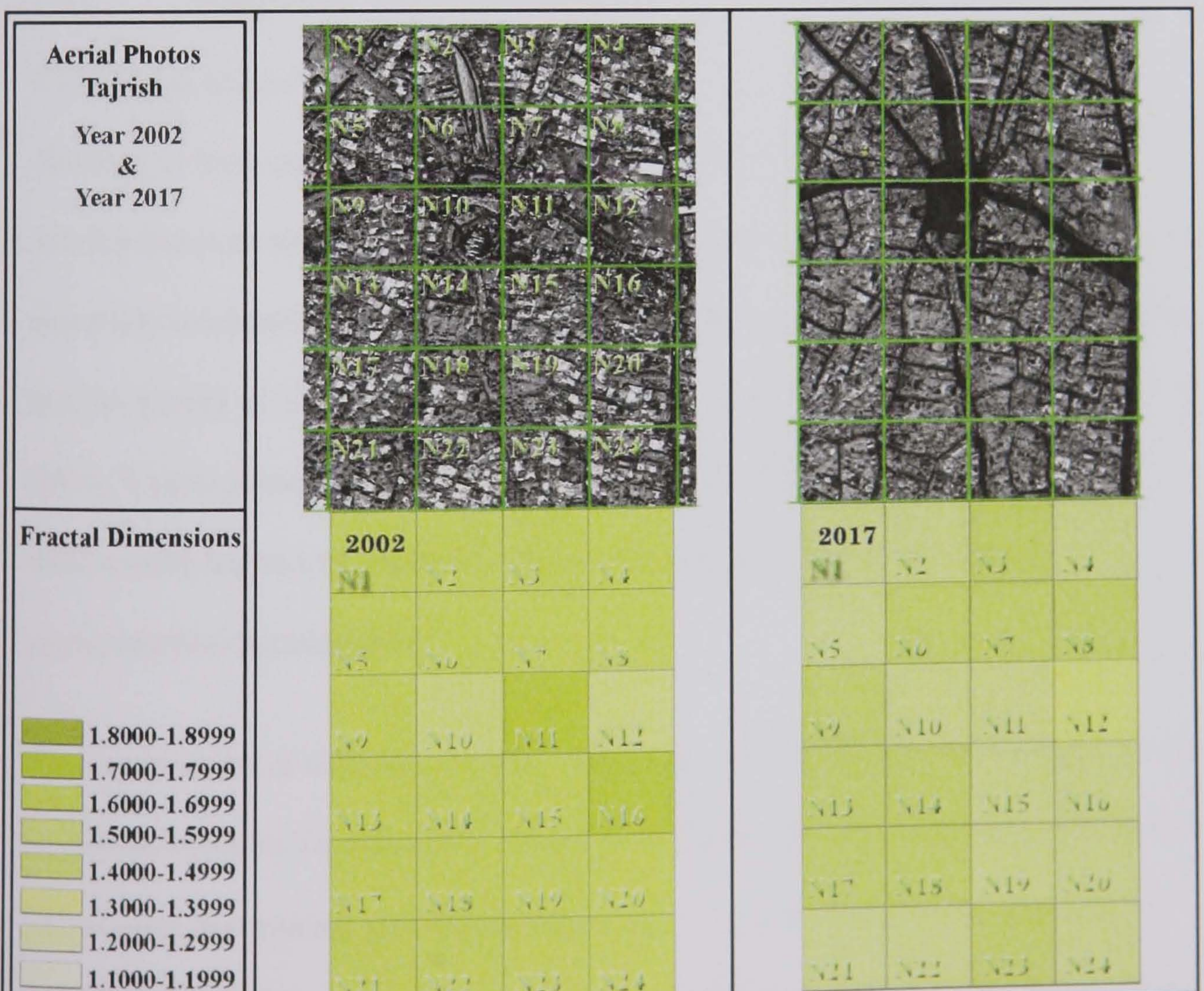


Figure 7.21: The degree of change in physical complexity of the neighbourhoods in Tajrish if the street widening policy is completed (e.g. by 2017).

The test reveals the impact of the street widening policy over 25 years. It indicates that the degree of physical complexity will change considerably, if this single plan is completely implemented. Both Table 7.8 and figure 7.21 clearly show a decrease in fractal dimensions of all neighbourhoods – particularly the oldest ones (e.g. N11 and N16). The result of fractal assessment also conforms to the statement, given by Alexander (2002b), that the application of linear geometry to an old context changes radically its physical characteristics and associates inevitably with thousands of mistakes (see Chapter Two, section 2.2.2).

7.3.3 Vegetation, physical complexity and environmental sustainability

While some architects and urban designers might have considered trees as minor elements in their designs or have left them to the interest of landscapers, recent developments in urban studies consider vegetation or green space at a local level as an important environmental criterion in terms of sustainable development, urban quality, and the quality of life (see Williams, Burton and Jenks, 2000; Brandon and Lombardi, 2005). Fractal dimension assessment could explain this and mathematically demonstrate the role of vegetation in maintaining physical complexity and environmental sustainability.

The examination of different samples in the case study of Shemiran in general, and the neighbourhoods in Tajrish and Velenjak in particular, revealed that fractal dimensions in the areas that contain significant vegetation are higher than those that do not. For instance, the neighbourhoods V-N1 and V-N19 in Velenjak have very similar urban patterns and building types, while the fractal dimension V-N19 is higher due to the amount of vegetation (figure 7.22).

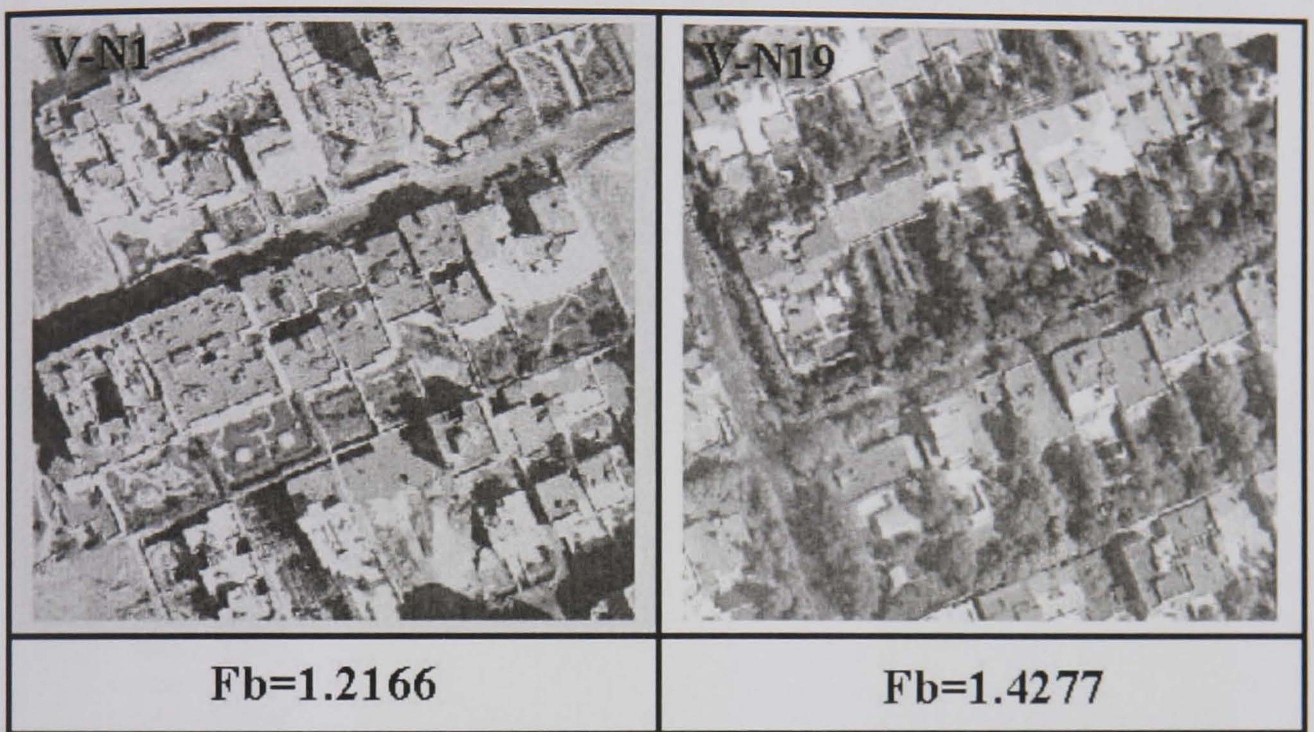


Figure 7.22: Aerial photos of V-N1 and V-N19 in Velenjak (2002) with similar plot layout and building type but different fractal dimensions.

The other way to examine the impact of vegetation on physical complexity is to compare the assessed fractal dimensions of a single neighbourhood at different periods. As seen earlier in the case of Tajrish-N1 (figure 7.17), the built components in this neighbourhood were unchanged between 1969 and 2002, while the decrease in the amount of vegetation caused a significant rise in fractal dimension. The impact of vegetation on spatial complexity can be observed more clearly if the same area is examined with and without trees. As the types of the trees in Tajrish are mainly deciduous, the best way for such a test is to compare the aerial photos in two different seasons. Figure 7.23 illustrates the aerial photos of Tajrish for winter 1965 and summer 1969 and their respective assessed fractal dimensions. There is little change in built environment and the trees will not have grown significantly in this period.

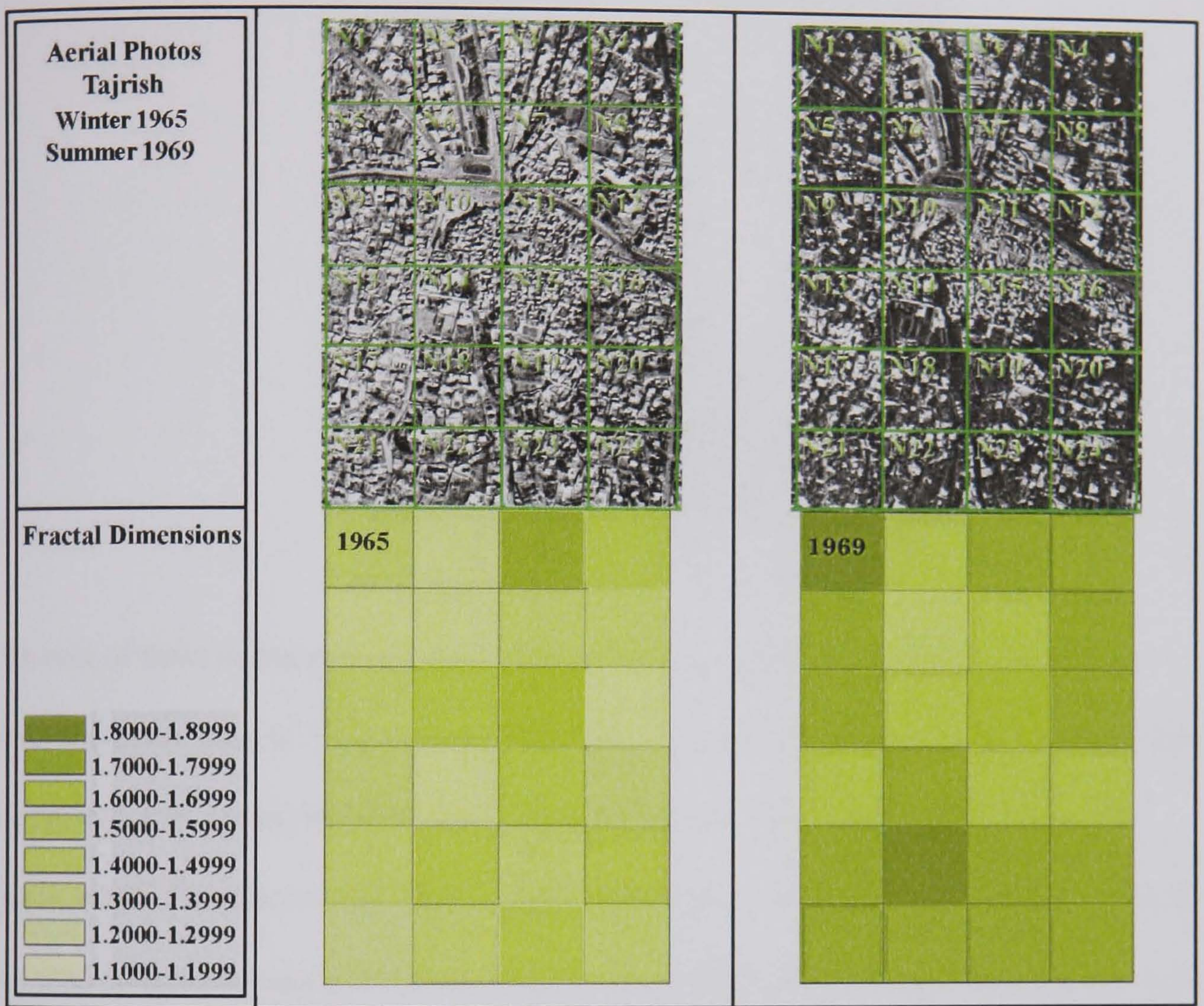


Figure 7.23: The aerial photos of Tajrish in winter 1965 and summer 1969. The fractal dimensions of many assessed neighbourhoods decreased in the winter.

As there is only a three and a half year difference between these two photos, the urban built form did not have noticeable changes. However, the test clearly indicates that the degree of physical complexity of many examined neighbourhoods increased during the summer. Only the complexity of the neighbourhoods which did not have trees (e.g. N10, N15), remained constant in different seasons. As figure 7.23 illustrates, some of the neighbourhoods such as N5, N9, N17, N19, and N24 demonstrate similar complexity in the summer, but their fractal dimensions vary in the winter. Therefore, another point can be concluded from the above test: trees can contribute to a balanced spatial complexity in the areas composed of diverse built components.

Figure 7.24: A view of Vali-e Asr Street. (the photo taken by the author, March 2008)

The role of trees in maintaining the balance of urban spatial complexity can also be observed in the case of Vali-e Asr Street. The land use map (figure 7.25, left) indicates the existence of varied building types and street patterns on both sides of Vali-e Asr Street, while the mature trees (figure 7.24; Appendix D, figure D.4) provide a balanced physical complexity along the street (figure 25, middle). Accordingly, a hypothesis could be developed claiming that natural elements such as trees would sustain the level of urban physical complexity in the areas where built elements might change frequently. The fractal assessment method can also give extra weight to the statement, written in Tehran's comprehensive plans, that the remaining gardens and mature trees in the case study of Shemiran are to be conserved as part of the natural heritage of the city (ACAUP, 2002).

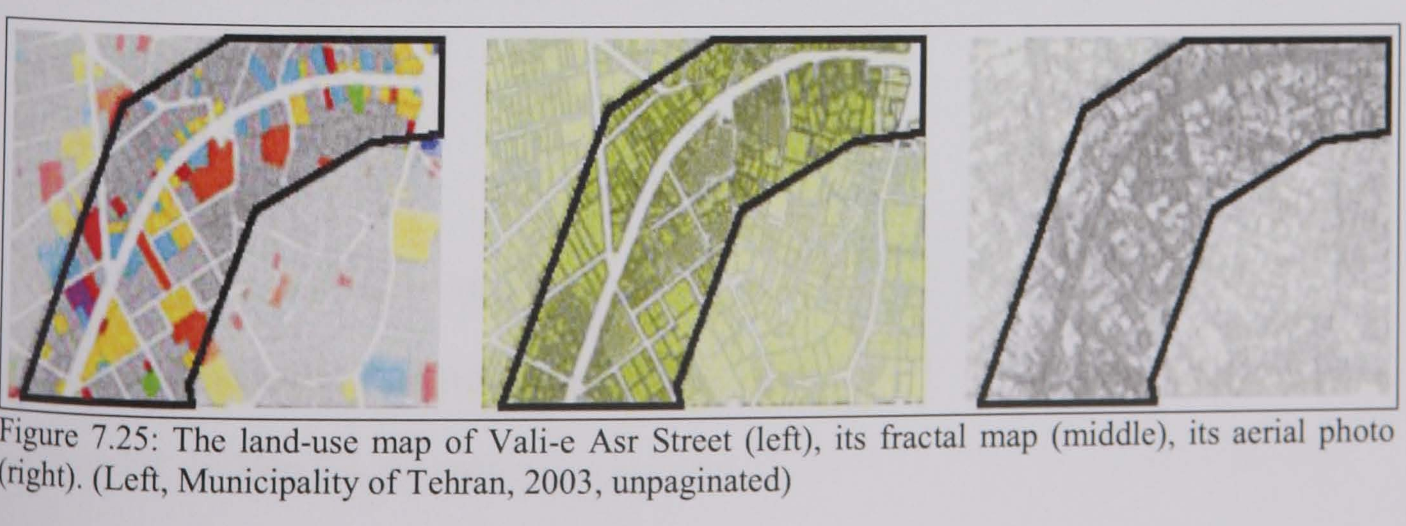


Figure 7.25: The land-use map of Vali-e Asr Street (left), its fractal map (middle), its aerial photo (right). (Left, Municipality of Tehran, 2003, unpaginated)

7.4 Chapter Summary

The results of the fractal measurements have been analysed quantitatively and illustratively in this chapter. The capabilities and advantages of the fractal analysis of urban patterns were discussed in terms of fractal identification, classification, and more importantly the examination of change over both place and time. Fractal maps were used as the basis for comparing, analysing, and interpreting urban patterns at different scale levels of the case study (with the emphasis on the neighbourhood scale).

In the first part of this chapter, the potential of the fractal approach in identifying urban patterns was discussed in terms of urban fingerprints and FNIDs. Fractal maps demonstrate the complexity of urban patterns while FNIDs mathematically identify such complexity. An FNID can be obtained by assessing fractal dimensions an urban element at different levels in the city hierarchical structure from neighbourhood to city scales. FNIDs can be used as a benchmark by which any changes to urban patterns in the future can be measured. For instance, urban conservationists who are keen to preserve urban characteristics can use FNIDs to suggest a range of acceptable changes in fractal dimensions for each designated areas. It is a more flexible appraisal method, sustaining morphological characteristics while allowing innovation and redevelopment in a historic urban context.

Another application of the proposed analysis method is the fractal classification of urban patterns. Having added the assessed fractal dimensions of different patterns to the database of ArcMap 9.2, the software could easily locate areas with a particular degree of complexity. Fractal classification is a quantitative method and, therefore, the number of classes could be easily increased or decreased according to the required precision of the research. In the second part of this chapter, the patterns were classified within three categories of low, medium, and high complexity and the characteristics of their respective neighbourhoods were explained. Fractal classification can assist planners to gain further insights into the complexity of urban forms in terms of pattern recognition.

The third part of the chapter focused on assessing and analysing the change in the urban pattern of Tajrish (the main case study) both as occurring gradually over time, or has been caused by urban interventions. Aerial photos of Tajrish from 1956 to 2002 were analysed to examine the change experienced by each of its 24 neighbourhoods experienced during this period and the results were interpreted. The results showed that time, natural, and geographical features are the most important factors influencing urban spatial complexity. Furthermore, a simple technique was devised to measure possible changes in the future (e.g. caused by a design proposal, or even an urban policy that has morphological consequences). The chapter also suggested the A-R-Technique to assess and predict such changes before their actual implementation. Urban specialists can then refer to the FNID of each neighbourhood to assess quantitatively the degree of change in its pattern caused by that urban intervention. As each individual neighbourhood has its own unique characteristics, it would then be the responsibility of decision makers to evaluate, judge, reject, or approve these changes.

In summary, the proposed fractal analysis method was found to be useful for pattern recognition in providing a better understanding of the nature of urban morphological evolution in the selected case studies. The same method can be applied to the entire metropolitan city of Tehran and more generally to any other city. Finally, it can be claimed that the fractal analysis of urban form is more precise and realistic than the conventional linear analysis based on Euclidean principles. Further outcomes and findings will be discussed in the following concluding chapter.

CHAPTER EIGHT

CONCLUSION

Introduction

The research achieved its main aims and objectives through three methodological stages of the research: literature review, case study examination, and analysis of results. The principles and applications of complexity theory and fractal geometry were compared to the linear principles of Euclidean geometry in order to examine the potentials and limitations of the conventional approach to urban forms, and to verify the advantages of the fractal approach in urban morphological studies (aim a and b). The research also developed a practical assessment technique to measure and map urban morphological complexities (aim c), exhibiting the homogeneity and heterogeneity of the patterns over time and place. The proposed fractal map provides a practical tool to identify, classify, and analyse emergent urban patterns (objective a), and to measure pattern changes over time (objective b). The fractal map and the fractal assessment method enable urban scholars and decision makers, as well as architects, urban planners and designers, to reflect better on their decisions and design proposals before their real implementation (objective c).

This final chapter concludes with an overall research summary. To outline the main findings, the outcomes of the literature review and the case study examination are summarised and the linkages between the previous chapters are highlighted. Then the advantages and limitations of the proposed fractal assessment technique will be addressed, both to highlight its contribution to new knowledge, and to create a platform for other researchers who are interested in developing the suggested technique and exploring the ideas in further detail. To put the research conclusion into context, the chapter begins with the research findings in relation to two set of questions raised in Chapter One.

8.1 The main findings from the research questions

The main findings can be addressed directly by referring to two set of questions raised at the beginning of this thesis (see Chapter One, section 1.2.2). The first set of general questions inquired about the credibility of the conventional geometry of straight lines (Euclidian geometry) in urban morphological analysis, the applications of the new theories of complexity and fractals, the properties of city systems as complex systems, and the failures of the top-down linear approach to complex urban systems (Questions 1, 2, 3, and 4). They were designed according to the research aims and were explored mainly through the literature review. The second set of specific questions covered the applicability of these concepts to urban morphological analysis such as how the complexity of urban forms and patterns can be measured or mapped, and how their changes over time can be assessed (questions 5, 6, and 7). The latter set was formulated to target the research objectives through the case study examination and analysis.

8.1.1 Euclidean geometry and morphological complexity

The research sought to identify the achievements and failures of the conventional geometry of straight lines (Euclidean Geometry) in designing, analysing, and interpreting urban forms (research aim a; see also question 1). In addressing this issue, the science of geometry in general, and the achievements of the conventional of geometry of Euclid in particular, were reviewed through a historical context (Chapter Two). As discussed, while Euclidean geometry can describe some aspects of architectural and urban design products in a city, particularly the parts that are designed or planned, it fails to interpret the complexity of unplanned forms, which are known as organic. The research established some reasons why a realistic insight into urban forms and their evolution over time would be beyond the simplicity of Euclidean geometry. They are summarised below:

1- Euclidean view describes the seemingly irregular organic forms as amorphous or disordered, while they exhibit patterns that are comprised of elements with strong hierarchies (semi-lattice not tree-like) usually initiated with some simple rules that reveal their underlying order (see Chapter three, sections 3.2.2.11, 3.3.3.2, and 3.3.4).
2- In most cases, cities were only planned in two (horizontal) dimensions. The third dimension is usually formed from many individual decisions at much smaller scales (architecture or urban design level). Even where some restrictions are applied to an urban facade by planning policies, the buildings' height and their facades are usually the product of a negotiated ever-changing design between individual owners and the planning authority. Therefore, in any case, the extent to which the third dimension is ordered or planned is always a matter of degree, which makes a city even more complex that cannot be easily interpreted by Euclidean shapes (see Chapter Two, section 2.2.1).
3- From architectural scales to city scales, the built environment is in a state of permanent morphological flux. Even the planned parts of a city are adapted to their context in ways that are more natural once the plan comes to be implemented; and

they evolve gradually according to the new needs and conditions. Therefore, all cities show some irregularity in most of their parts (see Chapter Two, section 2.2.1). While Euclidean geometry can analyse somehow the relationship between the components of an individual design product, understanding of the organic evolution, as the integration of many small forms and their changes over time, cannot be simply analysed by Euclidean principles.

4- From the design point of view, Euclidean geometry is only capable of creating linear relationships between the components of a design (an ornament, a building, a designed part of a city, *etc*), in which the resultant form cannot usually reach a high degree of complexity. Furthermore, while Euclidean geometry can impose order to an existing organic and complex urban context, simultaneously, it creates thousands of mistakes, as it reduces the complexity of the old context (see Chapter Two, section 2.2.2).

5- Non-integer fractal dimensions, which are the key criteria in measuring the degree of physical complexity of both natural and artificial forms, are more accurate than integer dimensions perceivable by Euclidian geometry (see Chapter Three, section 3.3.2).

8.1.2 The relationships between chaos, fractals and complexity

In Chapter Three, the research sought to find appropriate definitions for the terms complexity, chaos and fractals, and highlighted their main principles and properties as they appear in a complex system (research aim b; see also question 2). Chaos is the key term in understanding of complexity theory. Therefore, the research explored the concept through the contemporary physics as related to chaotic dynamics. As discussed, the Newtonian dynamics only responds to the mechanical universe, while chaotic dynamics can describe well the organic universe. Time is irreversible in chaotic systems (the arrow of time) and their status in any instant is very sensitive to their initial conditions (the butterfly effect). A complex system incorporates a number of chaotic systems, and becomes more complex as the time passes. That is perhaps why a complex system is defined as a system of complex systems (Batty, 2008). In this sense, chaos can be considered as the subset of complexity (Ward, 2003).

While there is not a generally accepted definition for the term complexity, this study identified twelve characteristics for a complex system by which the theory might be better understood. All of them can arguably also be observed in a city system (see Chapter Three, section 3.2.2). Therefore, cities are claimed to be complex systems. Fractals are considered as one of the properties of a chaotic complex system. In other words, the output image of the chaotic behaviours of the systems within a complex system is fractal. The notion of self-similarity and self-affinity were used to typify fractals. Linear and nonlinear fractals were introduced (see Chapter Three, section 3.3.3). It was argued that the patterns at small city scales are not exactly similar to the patterns at city large scales, and therefore, the urban patterns we observe in a city system are typified under nonlinear self-affine fractals. The key notion of non-integer fractal dimension was explained to reveal its potential to analyse organic forms. Chapter Three also identified some of the most common methods of measuring fractal dimensions.

Complexity theory and fractals have a wide applicability to many natural and artificial systems whose dynamics – the interactions of local agents – generate highly ordered global patterns. These theories explain the evolutionary dynamics of systems whose temporal and spatial "fingerprints" or "morphological signatures" are fractal. In short, it can be concluded that cities are good candidates for the application of complexity theory and fractal geometry as they exhibit the characteristics of complexity systems in an organic universe.

8.1.3 Fractal and non-fractal architecture

Having explained the failures of Euclidean principles and the advantages of fractal geometry in interpreting both natural and artificial forms, a basic but important question is whether fractal geometry is an essential substitute for Euclidean geometry as applied to architecture and urban design. This question was mainly explored in Chapter Four (section 4.1.3) under the notions of fractal and non-fractal architecture. Some designers and architects have applied the scaling rules of self-similarity to obtain a sort of design style – fractal style. However, in most cases, their design products have been misinterpreted as if they have fractal quality.

In fact, Euclidean quality is the intrinsic property of any design output, at all scales of design activities from product design to architectural and urban design. It is not possible to ask designers to put aside Euclidean principles while they are designing. Whether they use ruler, pencil on a drawing board, or CAD (Computer Aided Design), the process of their design is rather short, and the result is fabricated not generated. Only buildings or urban spaces that are generated through the process of adaption and comprise elements that are added or removed according to their environmental conditions and new needs can achieve a sort of fractal quality similar to what we see in natural phenomena. In short, fractal quality is achievable only out of long-generated processes, not short design processes.

Therefore, the immediate answer to the above question is 'no'. However, this research proposed some criteria by which a building or an urban space can be evaluated as fractal. it can be claimed that a piece of architecture or an urban space can be evaluated as fractal, if its fractal dimensions remain high at different scales of observation and the components of its hierarchical structure obtain more if not all these key features: integrity and multiplicity, self-similarity, hierarchies of connections, and change over time/space (see Chapter Four, section 4.1.3.2)

8.1.4 The bottom up nature of urban morphological evolution

Chapter Four also explored why the conventional top-down master planning and large-scale urban design proposals do not conform to the nature of urban morphological and functional evolution (aims a and b; see also question four). The same reasons established for the failure of Euclidian geometry can explain why urban interventions through large-scale urban design proposals and master plans should be avoided or done with extreme caution. It takes time for an individual designed building to adapt to its environmental conditions and to be configured according to the new needs once it has been implemented. Any element in an organic urban growth is the response to a need according to the local conditions, limitations, and restrictions applied over a long period in the history of that place. As time passes, that place becomes more and more complex. Therefore, time is the architect.

As discussed in the third part of Chapter Three, fractals are the outcomes of the interaction of a system with other systems within a complex environment. Such an interaction and its feedback loop require time. Computers may be able to run thousands of iterations to simulate a fractal shape similar to what we see in nature, but a real fractal shape cannot be created all at once. Therefore, the terms "fractal architecture" and "fractal city" should be understood under an incremental evolutionary process, not a short design process usually occurs in architectural or urban design studios (see also Chapter Four, section 4.1.3.2).

The degree of control over the scale of an urban intervention is also an essential criterion in the creation of complexity. It has been mentioned that the employment of Euclidean principles during the design process is inevitable, and therefore, the design products are virtually fabricated not generated irrespective of their scales. The larger the scale of an urban intervention, or the more control is imposed to an existing urban context, the less chance it has to respond to its local conditions, and the more it reduces the complexity of that place.

In short, the degrees of control over space/time scales play the main role in the creation of complexity in a city. In other words, there is less chance for complexity to emerge where there is a maximum degree of control over a large city scale and every piece is determined by its architect, planner, or urban designer, and when the processes of design and construction are relatively short. Therefore, the following guidelines can be concluded in order to sustain or enhance urban physical complexities:

1- Large-scale urban interventions should be avoided. The more we learn, perhaps the less we intervene.
2- Large-scale master plans should be frequently updated and revised through a bottom up process of organizational hierarchies.
3- An urban design proposal should be divided into the phases of smaller scale projects and be implemented one by one (not all at once) allowing revisions and refinements. Each phase is to be carried out only after the reflections from the local people are collected on the previous phases.
4- Small-scale projects are to be carried out with an extreme caution, particularly in old urban contexts.
5- The more the information gathered from the local conditions, and the more the means of public participation are provided in decision-makings, there is less possible that mistakes are made.

Such a conclusion can also be made from the planning perspective. It was extensively discussed in chapters Four and Five that the conventional top down planning approaches that have been widely applied during the twentieth century failed in understanding the complex nature of city forms and functions, and therefore, the methods taken from such views and implemented in practice failed to achieve their goals (see Chapter Four, section 4.2.1.1, and 4.2.1.2). The evidence shows that there is a big gap between the ideals of the master plans and the realities on the ground – both in Western and Eastern metropolitan cities (see Chapter 5, sections 5.1.3, and 5.1.4).

The failures of the master plans in metropolitan cities in general, and in the case study of Tehran in particular, conform to the outcome of the theoretical debate discussed in chapters One and Three, where the nature of cities is considered to be a problem in organised complexity (see also Chapter One, section 1.1.1). Twelve characteristics of complex systems and their analogical examples within urban systems establish reasons why a city should be viewed, studied, and treated as a self-organised complex system. A city system, as a complex system, is the concentrated action of millions of individuals and agencies that generate structures of complexity that are virtually impossible to predict, manage, control, or redesign effectively from the top down routine.

Some complexity theorists suggest a radical shift from top-down and centralized structures of government and management to much more decentralized organizations. Others propose a moderate suggestion, stating that an active complex systems planning is somewhere between the bottom up and top down processes of decision-making (see Chapter Four, section 4.2.1.2). While this research is closer to the latter suggestion, it should be stated that complex systems models are very new planning models (see also section 4.2.1.2.2) which are by no means complete. Therefore, further research is required to promote the models to a more applicable level.

8.1.5 Complexity theory and fractals as applied to urban form and function

One of the most basic and common questions about the complexity theory and fractal geometry is about their applicability to architecture, planning and urban deign, which is also a prerequisite for developing the fractal assessment tool at the research empirical stage (aim c, and objective a; see also question 5). Chapter Four addressed the new achievements in complexity theory in general, and in fractal geometry in particular, to explore this question. Increasing numbers of papers and projects suggest that the new theories of fractal architecture and fractal city can provide a firmer foundation for the critical ideas related to urban morphological and functional evolution. Table 4.1 in Chapter Four presented some of these applications. However, it was beyond the focus of this research to review them all; instead, Chapter Four provided some of the main examples under the three main themes of conceptualisation, simulation, and measurement.

While the fractal perception has impacts on all aspect of our everyday environment (see Chapter Three, section 3.3.6), the concept seems to be more applicable at the city and regional scales rather than architectural scales where there is a maximum level of control and all dimensions are determined by an architect. Therefore, from the design point of view, a degree of complexity that a designed building has achieved is a matter of degree. The degree of physical complexity in a design can be measured based on its fractal dimension. The research introduced some common methods of fractal measurement (see Chapter Three, section 3.3.5; and Appendix B). Chapter Four (sections 4.1.1.1 and 4.2.3) provided some examples about how fractal dimension can be used as a critical tool at architectural and urban design scales.

At city and regional scales, the "fractal city" is also a new concept developed during the last 15 years. Developments in urban simulation techniques are at its core. Computer-based simulation modelling (*e.g.* DLA, CA, and CP models) is based on a precise recognition of the non-linear character of city systems (see Chapter Four, section 4.2.2). It provides a new systems-founded rationalism in planning as a process. Although many efforts have been made to identify how complex city systems behave from the bottom up in theory and lab-modelling, they have not yet completely been accepted in planning policy and practice. Thus the conventional top-down process of decision-making – the hallmark of two planning transitions in the 20th century – is still dominant (see also Chapter Four, sections 4.2.1.1.1 and 4.2.1.1.2). Therefore, this research calls for a third transition in planning and design, advocating the developments made in complex systems planning.

8.1.6 Mapping and measuring complexity

In the light of the second and the third methodological stages (see Chapter one, sections 1.3.2.2 and 1.3.2.3), the research focused on the more specific questions related to the potentials of these concepts in analysing urban physical complexity (Chapter One, questions 5, 6, and 7). Thus the research, as its main target, developed a practical tool to measure, visualise, and map the complexity of urban patterns (aim c, and objective c). Two main steps of the case study selection and the assessment method preparation were carried out to achieve this target.

In Chapter Five, sample cases with diverse urban patterns were selected within the case study, the city of Tehran, to be examined at the research empirical stage. The morphology, the historical review, and the initial fractal analysis of 22 urban districts of Tehran revealed that Shemiran (in the north of Tehran) could provide the appropriate cases for the examination. The organic pattern of Tajrish (Shemiran's centre) and the planned urban patterns of Velenjak were selected for examination.

Chapter Six introduced the employed fractal assessment method and developed a technique to visualise and map urban complexity by employing the fractal calculation software (Benoit 1.3) linked with the GIS software (ArcMap 9.2). Benoit 1.3 offers different methods to calculate fractal dimensions, and this research found the box-counting method to be appropriate in assessing the complexity of urban patterns. The assessed fractal dimensions as numerical data were then transferred to ArcMap 9.2 to be visualised. A pilot study tested the validity and sensitivity of the employed technique (see Chapter Six, sections 6.2.1 and 6.2.2). At the pilot stage, the fractal calculation software was calibrated and the urban images were adjusted and prepared for examination. The research succeeded in producing a fractal map for the first time. The fractal map is, in fact, the visualised version of the urban physical complexity.

8.1.7 Fractal dimension as a mathematical criterion for urban pattern analysis

The research also used the fractal assessment tool to identify, classify, and analyse emergent urban patterns originating from both organic and planned types of growth within the case study (objective a). In chapters Three and Four (see sections 3.3.2 and

4.1.3.2), it was explained that fractal dimension provides a legitimate and accurate criterion indicating mathematically the degree of physical complexity (fractality) of the forms and patterns within a complex system such as a city (*e.g.* a higher fractal dimension indicates a higher degree of complexity). The research identified, classified, and compared fractally different urban patterns within the case study of Shemiran, Tehran. The method also provided the means of measuring the change occurring over time in the complexity of emergent urban patterns at neighbourhood and local scales.

There are quantitative and qualitative approaches to identification and classification of urban patterns. There are also different statistical and structural methods that can be categorised under each approach. In this research, the proposed fractal identification and classification methods can be addressed as a form of statistical quantitative approach to urban forms and patterns (see Chapter Seven, section 7.1.1 and 7.2.1). While each method might have its own advantages, they are usually limited to a particular morphological property and restricted to only one specified urban scale. However, the proposed fractal assessment method does not have such restrictions, and therefore can be applied to any morphological features or a combination of some urban elements at different scales in order to identify and classify mathematically the level of complexity underlying their structure.

In terms of fractal identification, the research developed the idea of Fractal Neighbourhood Identification (FNID) by assigning four sequential fractal dimensional sets assessed for each neighbourhood at the different scales of the hierarchical structure to which it belongs. Each set identifies mathematically the degree of complexity the urban pattern under one level of the city hierarchical structure from local to city scales (see Chapter Seven, section 7.1.2). Therefore, FNID comprises four fractal dimensional codes, which makes a unique ID for each neighbourhood.

Fractal dimension can also be used as a sensitive criterion for classifying the urban patterns. This research suggested a classification method by dividing the range of assessed fractal dimensions into eight classes (from 1.1000 to 1.8999), indicating the degree of morphological complexity that each part poses (see figure 6.11 in Chapter Six). The number of classes can also be adjusted by changing the number breakpoints while dividing the range of fractal dimensions. For instance, in Chapter Seven, the assessed fractal dimensions were divided into three ranges, a) lower than 1.4000, b) between 1.4000 and 1.6999, and d) above 1.6999, then the urban patterns were classified as low, medium, and high complexity respectively (see figures 7.5, 7.6, and 7.7 in Chapter Seven).

The same method has been employed to assess the change that a single neighbourhood experienced over time (objective b). For this purpose, instead of comparing the aerial photos of different locations, the aerial photos of different periods related to one location were compared. The change in physical complexity of Tajrish (the main case study) and its 24 neighbourhoods were assessed for the periods between 1956 and 2002.

8.2 The original contribution to new knowledge and the significance of the proposed method

8.2.1 Fractal maps

> 'We have all read stories about maps that revealed the locations of some hidden treasure. ...in this case [fractals], a map [itself] is the treasure.' (Clarke, 2004, unpaginated)

Fractal maps provided the main contribution to new knowledge. It was shown that the fractal dimension analysis of urban patterns has the potential to identify and classify mathematically the level of complexity underlying the city structure. A fractal map recognises visually such a complexity, and therefore, it can be considered as a kind of urban morphological fingerprint. Fractal maps are associated with fractal dimensions, which are different from a neighbourhood, a district, or a city to another. Therefore, they are unique for each part of a city, and can be considered as a new way of pattern identification.

The main advantage of fractal maps is their use in classifying urban patterns. For this purpose, the research converted the fractal attribute (the assed fractal dimension) of each neighbourhood to a fractal shape by the GIS data processor, ArcMap 9.2 (see Chapter Six, section 6.3.3). ArcMap 9.2 facilitates a process of making an update or a change to input data. As explained earlier, it also provides tools to adjust the numbers of the classes required by the user. Moreover, Fractal maps provide further information about the homogeneity and heterogeneity of urban patterns. For instance, figure 6.8 showed clearly the dispersion of the neighbourhoods with low and high physical complexity, or figure 7.8 marked the areas that the urban pattern began distorting (see chapters Six and Seven respectively). Furthermore, Fractal maps could illustrate the fuzzy boundaries between the different urban patterns and the way each class distributed within the case study. The urban pattern analysis by using fractal-mapping method has also some common advantages with the FNID method that are discussed in the following section.

8.2.2 FNIDs

FNIDs demonstrate mathematically the differences between urban patterns based on their assessed fractal dimension, and therefore, they can be considered as a kind of fractal signatures of urban patterns. FNIDs can also be used for fractal identification. However, it can be claimed that they are more accurate than the fingerprint version of fractal maps. The FNID method provides a unique ID for every neighbourhood (based on a unique set of fractal dimensions), by which all patterns can be differentiated. However, the fractal-mapping method emphasis on the similarities between the complexity of neighbourhood patterns (based on a range of fractal dimensions), by which they might be categorised under the same class. Nevertheless, both methods have some common advantages over other statistical quantitative methods. These can be are outlined as:

1- Accuracy: Both fractal map and FNID are based on measuring fractal non-integer dimensions, which are more accurate than the structural and statistical methods using Euclidean integer dimensions. As discussed in Chapter Seven (section 7.1.1), the conventional statistical methods are only capable of analysing simple shapes in planned or semi-planned patterns. Their restrictions to integer dimensions (0, 1, 2, and 3) prevent them to measure and analyse the complexity of urban forms in detail. Therefore, Non-integer dimensions suggested in terms of FNID are more accurate means of measurement both for planned and organic patterns.

2- Wide applicability: the other statistical methods are usually applied to one particular morphological property (*e.g.* to identify or classify street patterns). However, while the proposed fractal identification methods can be applied to any single urban element (see Table 6.1, in Chapter Six) or a combination of some elements. For instance, the proposed method in this research examined the aerial photos of the case study, which contain a mixture of urban elements.

3- Scale coverage: the other statistical approaches are usually restricted to only one specified urban scale, while the proposed fractal approach provides a realistic view to urban patterns by examining their complexity at different city scales. An FNID, in particular, suggests a set of fractal dimensions for a single neighbourhood assessed at four levels of a city (neighbourhood, local, district, and city levels).

4- Clarity: Some identification and classification methods may create ambiguity. For instance, one single pattern may be classified under different titles by different observers. However, the fractal ID provides a clear and common sense result independent of the eye of its observer.

5- Data availability and accessibility: one of the advantages of the proposed method is that it uses remote sensing photos of the city taken from aircraft or satellites as the main source of data. They are available for all cities around the World. Updated satellite photos are accessible via the internet and a copy of the aerial photo of a city or part of a city can usually be obtained from its local or nearest GIS centre.

8.2.3 The change analysis of urban patterns

The change analysis of urban morphological complexity over time is one of the areas in which little research has been attempted, and therefore it is the most important contribution of this research to new knowledge. The research devised a method to measure and visualise the physical complexity of the existing urban patterns within the case study (the present status). The same method was applied to the past and the future status of the studied patterns. For this purpose, the fractal dimensions of 24 neighbourhoods in Tajrish (the research main case study) were assessed from year 1956 to 2002. The analysis revealed that:

a) The changes imposed by the new shopping mall added to the old market (*bazaar*), and the urban interventions close to Tajrish Square (the bus terminal and the public car parking) are the main factors causing the fall in the degree of physical complexity of the studied neighbourhoods.

b) Urban vegetation (gardens, green yards, parks, *etc*) has had a positive role in sustaining urban physical complexity (see Chapter Seven, section 7.3.1).

Both architectural projects and urban design interventions may maintain or change the physical complexity of an existing urban context depending on whether their forms demonstrate the same degree of complexity as existing one or not. Therefore, the research suggested a simple technique (A-R-Technique) by which the future changes caused by design proposals can be assessed in the lab before their actual implementation (see Chapter Seven, section 7.3.2). FNIDs can be used as a controlling base point to direct urban new developments and interventions to be built within certain range of fractal dimensions. This will arguably provide an effective way to conserve urban qualities by a more accurate, and at the same time, more flexible method than the current tight restriction applied to the new developments within old urban contexts.

The fractal assessment and A-R-Technique also equips decision makers to test the urban policies, which might have direct or indirect morphological impacts. The proposed method assists them to reflect better on their decisions, and to choose an urban scenario, which may better adapt to the spatial complexity of an exiting urban pattern. In short, it can be claimed that the research could also contributed to new knowledge in terms of promoting the fractal assessment tool to a more practical level.

8.3 The research limitations

Through careful analysis and reflection of the research, three main areas have been identified as having a number of limitations. They are a) the nature of the research area and the methodology, b) aspects of case study examination, and c) the limitations of the proposed method. At points in the thesis, the limitations of individual methods and approaches related to these issues have been discussed. The purpose of this section is to summarise them and include other limitations that have been recognised.

8.3.1 The limitations of the research scope and the methodology

On reflection, the concept of urban complexity can be considered too broad. A city comprises diverse but interlinked complex systems, a variety of complex socio-economic forces, and different overlapped geo-morphological layers, which make the city even more complex and the concept of urban complexity more difficult to grasp. The research focused on the morphological aspects of complexity, and among various morphological features, it is limited to the analysis of complex urban patterns at the neighbourhood level of the case study.

Another limitation has been imposed by the research methodology. The research followed a quantitative approach, which is based on concrete objective surveys and quantitative data analysis of the case study. The nature of type of the methodology is that, it lacks subjectivity and qualitative judgment. Therefore, the evaluative questions about different urban pattern types, the quality of architectural or urban design products, and the response of the users of an urban space with high or low physical complexity are beyond the scope of this research. Even the fractal analysis method developed in this research should be considered as an assessment tool, not an evaluative one. This method will assist urban specialists to assess urban intervention proposals or even the urban policies, which has morphological impacts. Since each individual case has its own unique properties and characteristics, it would be then the role of decision makers to judge, evaluate, and approve any changes that would be caused by the proposals.

8.3.2 The limitations of the proposed method

The research succeeded in developing a practical fractal assessment tool for measuring the change in urban patterns and mapping morphological complexity. Both advantages and limitations of the employed method were discussed in Chapter Six (sections 6.1.4.1 and 6.1.4.2). The main aspects of the examination process and method, which limits the research results are summarised below:

1. The limits imposed by the fractal analysis software, Benoit 1.3: firstly, none of the available software programs can measure fractal dimensions of 3D urban spatial patterns; therefore, the research limits to 2D examination and analysis of the case studies. Secondly, the employed software only performs a binary – black and white – image analysis. Therefore, some of the gray scale data may be missed during examination. Thirdly, Benoit 1.3 accepts only bitmap image format as its input, therefore the program

cannot distinguish the difference between layers of information in an image. Therefore, the unnecessary data was removed manually from an image before examination, and manual data removal might associate with mistakes.

2. The data source: The higher resolution the aerial photos have, the more accurate result will be achieved. In the case of this research, some of the earlier aerial photos of Tajrish were of poor in quality. Therefore, the research was limited only to those with acceptable quality (years 1956, 1969, 1979, 2002).
3. The limits imposed by the GIS software, ArcMap 9.2: The process of importing data from Benoit software, adding attribute data, creating new shape-files, and projecting fractal maps by ArcMap 9.2 require a number of sequential steps to be undertaken (see figure 6.12 in Chapter Six). This is a difficult, lengthy process even for an expert operator. In this research, the process of producing a fractal map is applied to the selected cases in the north of Tehran. To produce a fractal map for the whole city, an intermediate software program is required that can be programmed in order to process the data automatically, or a team of operators are to be arranged that the task can be divided between them.

8.3.3 The limitations of the case study selection and examination

It is worth emphasizing that one of the main aims of this research was to compare the gradual change in "urban morphological pattern" with the rapid change caused by a new urban development or a kind of urban intervention. For this aim, only a limited number of neighbourhoods were examined within the case study district of Shemiran. This can be considered as one of the research limitations. If more sample cases could have been examined, a stronger conclusion would have been possible to be made about Tehran's patterns of growth and its evolution over time. As explained in the previous section, this would require a team of surveyors and operators, which was not available for this research.

The change in morphological complexity, which an architectural or urban design proposal imposed to an existing urban fabric, can be viewed and measured from different perspectives. The main perspectives are those at the street level of the case study including street elevations, street vistas, skylines, *etc*. This reveals another limitation of this research, since it examined the sample cases only from an aerial view by aerial photos. A comprehensive analysis of the change at local and neighbourhood scales calls for a detailed examination of the urban elements from different street views.

8.4 Recommendations for future research

8.4.1 Opportunities for further research based on the research literature review

A study is rarely considered an isolated piece of intellectual activity separated from other similar investigations (Oliver, 2004). It adds to previous studies and usually acknowledges that other research required. During the last three decades, several researchers have explored the different aspects of city complexity. This research attempted to take an incremental step forward and add to the previous research by redefining the key terms in complexity theory such as chaos, fractal architecture, urban complexity, complex systems planning, and design.

However, none of these aspects is yet sufficiently explored. Our knowledge about the nature of urban evolution and complexity is by no means complete. Moreover, there are still gaps between these new concepts and their applications to urban form and function. Further research is required, enabling us to conceptualise, model, simulate, and measure better the city complexity. The more we explore, the more we understand how a city system behaves, and the better we are prepared to plan, design, and form our environment.

Several research ideas can be addressed directly from the outcomes of the literature review. Here are some examples:

- The long-established linear principles of Euclidean geometry still dominate the daily fabrication processes of society by architects and urban experts. More research is required to shift the traditional view to what is more real, to which can be termed fractal view.
- The twelve properties of a complex urban system – identified in Chapter Three (section 3.2.2) – require further research. The relationship between each property and its morphological analogy suggests an interesting research topic. A number of issues that discussed in Chapter Four (section 4.1.2.2) are also to be explored in more detail.
- A list of five criteria is proposed to define the term fractal architecture. As discussed in Chapter Four (4.1.3.2), this list is not complete. Further research is

required to evaluate whether a piece of architecture or an urban design product have fractal quality similar to what is seen in nature.

- The second part of Chapter Four called for a third transition in planning theory based on the principles of complex systems theory. There are still many gaps at conceptual and practical levels. There are only limited numbers of complex system planning models proposed so far, and they are still at their preliminary research stages. Further research is required to complete these models and to promote them to practical planning level.
- The current simulation and fractal measurement methods are not yet embedded in bottom up planning procedure. More research is required to fill the gap between the theories and the practice.

The fractal assessment technique developed during the course of this research can be considered as one of the tools required during bottom up planning procedures. It can be employed to measure the change in physical complexity imposed by individual design proposals, small or large urban interventions, and even the urban design policies, which have direct or indirect morphological impacts on urban patterns. These also have impacts on other urban aspects such as socio-economic patterns, which are also important. Thus, further interdisciplinary research is required to cover these issues and examine urban complexity from diverse perspectives.

8.4.2 Opportunities for further research based on the advantages and limitations of the proposed fractal assessment method

Both limitations and advantages of the proposed fractal assessment method provide opportunities for further research. They can be addressed under the following two questions: 'how can a fractal map be created more accurately?', and 'what are the other applications of the proposed method?' The first question calls for the aspects of the proposed method, which are required developments in order to create high quality fractal maps and to assess more accurately urban complexity. The second question addresses the potentials of this method to assess the other elements and features of urban morphology – other than those described in this research.

In section 8.3.2, the limitations of the employed method were outlined. More research is required to develop a kind of software program for 3D fractal analysis of urban forms. Arial and satellite photos contain very useful information about urban complexity, the current binary image analysis misses a range of the gray scale data. More developed software is required enabling us to process different data layers of complexity exhibited by gray scale and ideally colour scale images. The accuracy of the produced fractal maps in particular, and fractal analysis in general, also depend on the quality of the urban photos. The new development in digital and panoramic photography suggests a promising future.

The proposed method is semi computerised and parts of data processing had to be carried out manually (see figures 6.6 and 6.7 respectively) and transferring fractal data to ArcMap 9.2 required considerable amount of time. An intermediate software program can be developed and programmed in order to process the data automatically. Nevertheless, adding fractal data (fractal attribute) to the GIS database suggests new and unique opportunities for further morphological research on the case study, which have been previously impossible. Fractal attribute can be compared with any other available urban GIS attributes to find out where two different attributes are coexisted. This can be performed by filtering capabilities of ArcMap 9.2.

For filtering, only one urban element, or urban feature is selected and its respective attribute table is turned on, the others are turned off. For instance, the layers of natural urban forms (*e.g.* parks and gardens) can be filtered in order to analyse the fractal property of the built urban forms. Reversely, only natural features can be turned on to examine whether these area are generally exhibits high degree of complexity (fractality). In addition, the plots' and blocks, attributes such as size, density, and land use can be compared with their respective fractal attributes. For instance, the location of the plots with the area sizes lower than 300 square metres can be easily identified and be examined whether these plots exhibit generally low or high degree of physical complexity.

A number of topics and hypothesises are also developed during the course of this research that required further case study examination. For example, urban vegetation and trees in particular were found to play an important role in maintaining the physical sustainability of the examined areas. Further research is required in order to generalise this finding and to examine the implication of finding that tree planting will increase the fractal complexity of an urban space. Another recommended hypothesis that can be examined is that:

1) In the part of the case study where its neighbourhoods display more morphological order based on the range of the land-uses, sizes, and the age

of their buildings, the fractal dimensions of its hierarchical structure (FNIDs) are expected to be similar.

The hypothesis can also be reversed as follows:

2) The part of the case study, where the fractal dimensions of their hierarchical structures (FNIDs) are similar, it is expected that its components display morphological order and homogeneity based on the range of land-uses, sizes, and age of its buildings.

Finally, this research claims that the proposed method is universal and can be applied to any other cities. Further research is required to validate scientifically this claim. FNIDs can be assigned and fractal maps can be produced for all cities. Two different cities can be compared according to their respective fractal IDs. Moreover, a city or a part of it, where its historical records are available, can be analysed with this method to examine whether it succeeded to maintain its structural complexity over time or not.

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APPENDIX A

A GLOSSARY

OF

URBAN COMPLEXITY

Adaptation

'In the theory of Darwinian Evolution, adaptation is the ongoing process by which an organism becomes "fit" to a changing environment.... A fundamental characteristic of complex, adaptive systems is their capacity to adapt by changing the rules of interaction among their component agents. In that way, adaptation consists of "learning" new rules through accumulating new experiences' (Goldstein, 2001, unpaginated).

Adaptive Redevelopment

'A redevelopment a plot, a series of plots, within the existing street system without the introduction of new streets' (Conzen, 1960, pp.69, 95, 123; quoted in Larkham and Jones, 1991, p.13).

Agents of Change

'Agent; Agent of change; Amenity group; Applicant; Builder; Consultant; Depositor; Developer; Developer agent; Estate agent; Initiator; Institution; Original rural landholder; Owner; Planner/planning officer; Speculator/speculative developer; Subdivider' (Larkham and Jones, 1991, p.10).

Agent-Based Models

'Systems composed of individuals who act purposely in making locational/spatial decisions' (Batty, 2008, p.2).

Attractors

(1) 'The idea of attractor deals with "phase/state/condition space". In the development of a dynamical system over time we have attractors if the systems' trajectory does not move through all the possible parts of an n+1 (the +1 representing time) state space, but instead occupies a restricted part of it' (Byrne, 1998, p.168).

(2) 'The evolution of a nonlinear, dynamical, complex system can be marked by a series of phases, each of which constrains the behaviour of the system to be in consonance with a reigning attractor(s).... The dynamics of the system as well as current conditions determine the system's attractors. When attractors change, the behaviour in the system changes because it is operating under a different set of governing principles. The change of attractors is called bifurcation, and is brought about from far-from-equilibrium conditions which can be considered as a change in parameter values toward a critical threshold' (Goldstein, 2001, unpaginated).

Bifurcation

(1) 'A process whereby divergent paths are generated in a trajectory of change in an urban system' (Batty, 2008, p.2).

(2) 'The emergence of a new attractor(s) in a dynamical, complex system that occurs when some parameter reaches a critical level (a far-from-equilibrium condition). For example in the logistic equation or map system, bifurcation and the emergence of new attractors take place when the parameter representing birth/death rates in a population reaches a critical value. More generally, a bifurcation is when a system shows an abrupt change in typical behaviour or functioning that lasts over time' (Goldstein, 2001, unpaginated; see also Chapter Three, figures 3.6, 3.7, and 3.8).

Building Adaptation

'This is a particularly wide-ranging category, much subdivided, covering all changes to the building fabric rather than new building/major rebuilding/ redevelopment' (Larkham and Jones, 1991, p.23).

Building Pattern

'In town-plan analysis, "this is the arrangement of existing buildings, *i.e.* their block-plans in a built-up area viewed as a separate element complex of the town plan' (Conzen, 1969, p.123; quoted inLarkham and Jones, 1991, p.24).

Butterfly Effect

'A popular image portraying the property of sensitive dependence on initial conditions in chaotic systems, *i.e.*, a small change having a huge impact like a butterfly flapping its wings in South America eventually leading to a thunderstorm in North America.... The Butterfly Effect introduces a great amount of unpredictability into a system since one can never have perfect accuracy in determining those present conditions which may be amplified and lead to a drastically different outcome than expected. However, since chaotic attractors are not random but operate within a circumscribed region of phase or state space, there still exists a certain amount of predictability associated with chaotic systems. Thus, a particular state of the weather may be unpredictable more than a few days in advance; nevertheless, climate and season reduce the range of possible states of the weather, thereby, adding some degree of predictability even into chaotic systems' (Goldstein, 2001, unpaginated; see Chapter Three, sections 3.1.1.3 and 3.2.2.5).

Chaos

'A type of system behaviour appearing random-like, yet is actually deterministic and is constituted by a "hidden" order or pattern. Chaos can be found in certain nonlinear dynamical systems when control parameters surpass certain critical levels. The emergence of chaos suggests that simple rules can lead to complex results. Such systems are constituted by nonlinear, interactive, feedback types of relationships among the variables, components, or processes in the system' (Goldstein, 2001, unpaginated; see Chapter Three, section 3.1).

City Size Distribution

'A set of cities by size, usually population, often in rank order' (Batty, 2008, p.2).

Deterministic system

'A dynamic is determinist if knowledge of it and of the initial state of a system is all we need to know to predict the future of the system. Note that this is a matter in principle. In chaotic determinism we cannot know the initial state of the system with sufficient precision to predict its future trajectory' (Byrne, 1998, p.171).

Element Complex/Form Complex

'The totality of plan elements of one particular kind in a town plan viewed separately from others. There are three element complexes, *i.e.* the street system, the plot pattern and the building pattern' (Conzen, 1969, p.125; quoted in Larkham and Jones, 1991, p.37).

Emergent Patterns/ Emergent Properties

'The arising of new, unexpected structures, patterns, processes, [or properties] in a self-organizing system' (Goldstein, 2001, unpaginated). For instance, in the case of a city system, 'land uses or economic activities which follow some spatial order' (Batty, 2008, p.2).

Entropy

'The concept of Entropy refers to the tendency of things to move toward greater disorder, or disorganization rather than maintaining order. It refers to the importance of having an open system to import energy, information and materials, which can be used to offset the tendency toward disorganization. The second law of thermodynamics describes the Entropy. The law states that heat dissipates from a central source and the energy becomes degraded, although total energy remains constant' (Flood, 1993, p.12).

Entropy Maximizing

'The process of generating a spatial model by maximizing a measure of system complexity subject to constraints' (Batty, 2008, p.2).

Equilibrium

'A state of the urban system which is balanced and unchanging' (Batty, 2008, p.2).

Exponential Growth

'The process whereby an activity changes through positive feedback on itself' (Batty, 2008, p.2).

Far-from-equilibrium

'The term used by the Prigogine School for those conditions leading to self-organization and the emergence of dissipative structures. Far-from-equilibrium conditions move the system away from its equilibrium state, activating the nonlinearity inherent in the system. Far-from-equilibrium conditions are another way of talking about the changes in the values of parameters leading-up to a bifurcation and the emergence of new attractor(s) in a dynamical system. Furthermore, to some extent, far-from-equilibrium conditions are similar to "edge of chaos" in cellular automata' (Prigogine and Stengers, 1984; quoted in Goldstein, 2001, unpaginated).

Fast Dynamics

'A process of frequent movement between locations, often daily' (Batty, 2008, p.2).

Feedback

(1) 'The process whereby a system variable influences another variable, either positively or negatively' (Batty, 2008, p.2).

(2) 'The mutually reciprocal effect of one system or subsystem on another. Negative feedback is when two subsystems act to dampen the output of the other.... Positive feedback means that two subsystems are amplifying each other's outputs' (Goldstein, 2001; see Chapter Three, section 3.2.2.4).

Fractal Structure

'A pattern or arrangement of system elements that are self-similar at different spatial scales' (Batty, 2008, p.2; see Chapter Three, section 3.3).

Fractal Dimension

'A non-integer measure of the irregularity or complexity of a system. Knowing the fractal dimension helps to determine the degree of complexity and pinpoint the number of variables that are key to determining the dynamics of the system' (Goldstein, 2001, unpaginated; see Chapter Three, section 3.3.2).

Geometrical Analysis

'Analysis of plots, particularly medieval burgages, with especial reference to relative proportions of width and length' (Slater, 1990a, pp.74-77; quoted in Larkham and Jones, 1991, p.43).

Grid Plan/Gridiron Layout

'A rectilinear layout of streets and street blocks. It has been the mark of the founded town since ancient times, producing an efficient circulation system, and distribution of equal rectangular plots' (Larkham and Jones, 1991, p.44).

Initial Conditions

'The state of a system at the beginning of a period of observing or measuring it' (Goldstein, 2001, unpaginated).

Initiator

(1) 'This is a popular term used to describe the person or organization upon whose behalf a fabric change is initiated' Larkham and Jones, 1991, p.46).

(2) The initial step/level from which a fractal shape is constructed (Peitgen *et al*, 2004, p.89; see also Chapter Three, section 3.3.2).

Interaction

(1) 'The mutual effect of components or subsystems or systems on each other. This interaction can be thought of as feedback between the components as there is a reciprocal influence' (Kauffman, 1993; quoted in Goldstein, 2001, unpaginated).

(2) In a complex system, '... the effect of two or more variable causes acting together is not simply the some of their effects taken separately. Instead, we find that there are complex emergent properties' (Byrne, 1998, p.173).

Land Use Transport Model

'A model linking urban activities to transport interactions' (Batty, 2008, p.2).

Life Cycle Effects

'Changes in spatial location which are motivated by aging of urban activities and populations' (Batty, 2008, p.2).

Linear System

'A linear system is one in which small changes result in small effects, and large changes in large effects. In a linear system, the components are isolated and non-interactive. Real linear systems are rare in nature since living organisms and their components are not isolated and do interact' (Goldstein, 2001, unpaginated).

Local Neighbourhood

'The space immediately around a zone or cell' (Batty, 2008, p.2).

Logistic Equation

'An equation that has been applied to various natural systems such as the changes in a system's population over time which show a convergence to some fixed value or values over time' (Goldstein, 2001; see also Chapter Three, equation 3.2).

Logistic Growth

'Exponential growth capacitated so that some density limit is not exceeded' (Batty, 2008, p.2).

Lognormal Distribution

'A distribution which has fat and long tails which is normal when examined on a logarithmic scale' (Batty, 2008, p.2).

Micro simulation

'The process of generating synthetic populations from data which is collated from several sources' (Batty, 2008, p.2).

Model Validation

'The process of calibrating and testing a model against data so that its goodness of fit is optimized' (Batty, 2008, p.2).

Morphological Processes

'The set of process shaping urban form. These include adaptive, additive, repletive and transformative processes' (Larkham and Jones, 1991, p.55).

Multipliers

'Relationships which embody n'th order effects of one variable on another' (Batty, 2008, p.2).

Network Scaling

'The in-degrees and out-degrees of a graph whose nodal link volumes follow a power law' (Batty, 2008, p.2).

Nonlinear System

'A system in which small changes can result in large effects, and large changes in small effects. Thus, sensitive dependence on initial conditions in chaotic systems illustrates the extreme nonlinearity of these systems' (Goldstein, 2001, unpaginated).

Phase Space/State Space/Condition Space

(1) 'An abstract mathematical space which is used to display time series data of the measurements of a system' (Goldstein, 2001, unpaginated).

(2) 'If there are n variables, there will be n dimensions. The state space of the system at any instant can be describe by its co-ordinates in this n dimensional space with the measured value for each variable aspect being the co-ordinate for that dimension' (Byrne, 1998, p.173).

Plot Pattern

'The arrangement of plots – considered separately from the other plan elements – up to the level of street blocks' (Larkham and Jones, 1991, p.65).

Population Density Profile

'A distribution of populations which typically follows an exponential profile when arrayed against distance from some nodal point' (Batty, 2008, p.2).

Power Laws

(1) 'Scaling laws that order a set of objects according to their size raised to some power' (Batty, 2008, p.2).

(2) 'A type of mathematical pattern in which the frequency of an occurrence of a given size is inversely proportionate to some power (or exponent) of its size' (Bak, 1996; quoted in Goldstein, 2001, unpaginated; see also Yanguang and Yixing, 2004).

Rank Size Rule

'A power law that rank orders a set of objects' (Batty, 2008, p.2).

Reaction-Diffusion

'The process of generating changes as a consequence of a reaction to an existing state and interactions between states' (Batty, 2008, p.2).

Residential Density/Housing Density

'The number of houses per unit of land including the plots and all streets providing direct access to them. The term applied to an individual plot as well as to a plan unit. In the latter case, it is an average value' (Conzen, 1969, pp.129-130; quoted in Larkham and Jones, 1991, p.70).

Scale/Scaling Law

'The level at which a system is observed. For example, one can observe the coast of England from a satellite or from a jet liner or from a low flying plane, or from walking along the coast, or from peering down into the sand and rock of a cove beach you are standing on. Each of these perspectives is of a different scale of the actual coast of England. Fractals are geometric patterns that are self-similar on different scales' (Kaye, 1989; quoted in Goldstein, 2001, unpaginated).

Scale-free Networks

'Networks whose nodal volumes follow a power law' (Batty, 2008, p.3).

Segregation Model

'A model which generates extreme global segregation from weak assumptions about local segregation' (Batty, 2008, p.3).

Self-organisation

'A process in a complex system whereby new emergent structures, patterns, and properties arise without being externally imposed on the system. Not controlled by a centralized, hierarchical "command and control" centre, self-organization is usually distributed throughout a system' (Goldstein, 2001, unpaginated).

Self-organized Criticality (SOC)

'… a phenomena of sudden change in physical systems in which they evolve naturally to a critical state at which abrupt changes can occur. That is, when these systems are not in a critical state, i.e., they are characterized by instability, output follows from input in a linear fashion, but when in the critical state, systems characterized by self-organized criticality act like nonlinear amplifiers, similar to but not as extreme as the exponential increase in chaos due to sensitive dependence on initial conditions' (Bak, 1996; Waldrop, 1992; quoted in Goldstein, 2001, unpaginated).

Simulation

'The process of generating locational distributions according to a series of sub-model equations or rules' (Batty, 2008, p.3).

Slow Dynamics

'Changes in the urban system that take place over years or decades' (Batty, 2008, p.3).

Social Physics

'The application of classical physical principles involving distance, force and mass to social situations, particularly to cities and their transport' (Batty, 2008, p.3).

Spatial Interaction

'The movement of activities between different locations ranging from traffic distributions to migration patterns' (Batty, 2008, p.3).

Strange Attractor

'An attractor of a chaotic system which is bound within a circumscribed region of phase space yet is aperiodic, meaning the exact behaviour in the system never repeats. The structure of a strange attractor is fractal.... A strange attractor portrays the characteristic of sensitive dependence on initial conditions (the Butterfly Effect) found in chaos' (Goldstein, 2001, unpaginated).

Trip Distribution

'The pattern of movement relating to trips made by the population, usually from home to work but also to other activities such as shopping' (Batty, 2008, p.3).

Urban Hierarchy

'A set of entities physically or spatially scaled in terms of their size and areal extent' (Batty, 2008, p.3).

Urban Morphogenesis

'The creation of physical forms viewed as a developmental or evolutionary process' (Whitehand, 1981, pp.1-24; quoted in Larkham and Jones, 1991, p.54).

Urban Morphology

(1) 'Patterns of urban structure based on the way activities are ordered with respect to their locations' (Batty, 2008, p.3).

(2) 'The study of the physical (or built) fabric of urban form, and the people and processes shaping it' (Larkham and Jones, 1991, p.55).

Urban System

'A city represented as a set if interacting subsystems or their elements' (Batty, 2008, p.3).

APPENDIX B

FRACTAL MEASUREMENT METHODS

TruSoft-international (2004), the company produced Benoit 1.3, provided the following explanation for all five measurement methods including those discussed in Chapter Three (section 3.3.5) to show the mathematical principle behind the software:

B.1 Box Dimension Estimation Method interface

The box dimension is defined as the exponent Db in the relationship:

$$N(d) \approx \frac{1}{d^{Db}} \qquad \text{(equation 1)}$$

N(d) is the number of boxes of linear size d necessary to cover a data set of points distributed in a two-dimensional plane. The basis of this method is that, for objects that are Euclidean, equation (1) defines their dimension. One needs a number of boxes proportional to 1/d to cover a set of points lying on a smooth line, proportional to 1/d^2 to cover a set of points evenly distributed on a plane, and so on.

This dimension is sometime called grid dimension because for mathematical convenience the boxes are usually part of a grid. One could define a box dimension where boxes are placed at any position and orientation, to minimize the number of boxes needed to cover the set. It is obviously a very difficult computational problem to find among all the possible ways to cover the set with boxes of size d the configuration that minimizes N(d). Also, if the overestimation of N(d) in a grid dimension is not a function of scale (i.e., we overestimate N(d) by, say, 5% at all box sizes d), which is a plausible conjecture if the set is self-similar, then using boxes in a grid or minimizing N(d) by letting the boxes take any position is bound to give the same result. This is because a power law such as (1) is such that the exponent does not vary if we multiply N(d) or d by any constant.

In practice, to measure Db one counts the number of boxes of linear size d necessary to cover the set for a range of values of d; and plot the logarithm of N(d) on the vertical axis versus the logarithm of d on the horizontal axis. If the set is indeed fractal, this plot will follow a straight line with a negative slope that equals -Db. To obtain points that are evenly spaced in log-log space, it is best to choose box sizes d that follow a geometric progression (e.g. d = 1, 2, 4, 8,...), rather than use an arithmetic progression (e.g. d = 1, 2, 3, 4,...).

A choice to be made in this procedure is the range of values of d. Trivial results are expected for very small and very large values of d. A conservative choice may be to use as the smallest d ten times the smallest distance between points in the set, and as the largest d the maximum distance between points in the set divided by ten. Alternatively, one may exceed these limits and discard the extremes of the log-log plot where the slope tends to zero.

In theory, for each box size, the grid should be overlaid in such a way that the minimum number of boxes is occupied. This is accomplished in Benoit by rotating the grid for each box size through 90 degrees and plotting the minimum value of N(d). Benoit permits the user to select the angular increments of rotation.

B.2 Perimeter-Area Dimension Estimation method interface

Consider an object that is a closed loop in the two-dimensional plane, e.g., an island. Suppose that this island is a Euclidean object, i.e., a circle. Then the area A and the perimeter P of such an island are related as follows:

$$p = 2\pi r = r\sqrt{\pi A} \approx \sqrt{A}$$
$$A = \pi r^2 = \frac{p^2}{4\pi} \approx p^2 \qquad \text{(equation 2)}$$

"r" is the radius of the circle; note that the proportionality between A and P does not depend on r. If the island had a fractal perimeter, then the relationships (2) become

$$p \approx (\sqrt{a})^{Dp} = A^{Dp/2}$$
$$A \approx p^{2/Dp} \qquad \text{(equation 3)}$$

Dp is the perimeter-area dimension. Indeed, if Dp = 1, one obtains the Euclidean case, as in (2); if Dp = 2, then the figure is space-filling because P A. If Dp is between 1 and 2, equation (3) shows that the perimeter of the fractal figure is longer than the perimeter of a Euclidean figure with the same area, as expected.

In practice, to estimate Dp one measures perimeter P and area A with boxes of different side length d, and plots the logarithm of A on the vertical axis versus the logarithm of P on the horizontal axis. If the relationship is indeed fractal, this plot will follow a straight line with a positive slope that equals 2/Dp. Note that the estimation of perimeters and areas has to be done over a range of d.

B.3 Information Dimension Estimation Method

This fractal dimension is often encountered in the physics literature, and is generally different from the box dimension. In the definition of box dimension, a box is counted as occupied and enters the calculation of N(d) regardless of whether it contains one point or

a relatively large number of points. The information dimension effectively assign weights to the boxes in such a way that boxes containing a greater number of points count more than boxes with less number of points.
The information entropy I(d) for a set of N(d) boxes of linear size d is defined as

$$I(d) = -\sum_{i=1}^{N(d)} m_i \log(m_i) \qquad \text{(equation 4)}$$

where mi is:

$$m_i = \frac{M_i}{M} \qquad \text{(equation5)}$$

Mi is the number of points in the i-th box and M is the total number of points in the set.

Consider a set of points evenly distributed on the two-dimensional plane. In this case, we will have:

$$N(d) \approx \frac{1}{d^2} \qquad m_i \approx d^2 \qquad \text{(equation 6)}$$

so that (4) can be written as:

$$I(d) \approx -N(d)[d^2 \log(d^2)] \approx -\frac{1}{d^2}[2d^2 \log(d)] = -2\log(d) \qquad \text{(equation 7)}$$

For a set of points composing a smooth line, we would find: $I(d) \approx -\log(d)$

Therefore, we can define the information dimension Di as in:

$$I(d) = -D_i \log(d) \qquad \text{(equation 8)}$$

In practice, to measure Di one covers the set with boxes of linear size d keeping track of the mass mi in each box, and calculates the information entropy I(d) from the summation in (4). If the set is fractal, a plot of I(d) versus the logarithm of d will follow a straight line with a negative slope equal to -Di.

At the beginning of this section, we noted that the information dimension differs from the box dimension in that it weighs more heavily boxes containing more points. To see this, let us write the number of occupied boxes N(d) and the information entropy I(d), in terms of the masses mi contained in each box:

$$N(d) = \sum_i m_i^0$$
$$I(d) = -\sum_i m_i \log(m_i) \qquad \text{(equation 9)}$$

The first expression in (9) is a somewhat elaborate way to write N(d), but it shows that each box counts for one, if mi > 0. The second expression is taken directly from the definition of the information entropy (4). The number of occupied boxes, N(d), and the information entropy I(d) enter on different ways into the calculation of the respective dimensions, it is clear from (9) that:

$$Db \leq Di \qquad \text{(equation 10)}$$

The condition of equality between the dimensions (10) is realized only if the data set is uniformly distributed on a plane.

B.4 Mass Dimension Estimation Method

Draw a circle of radius r on a data set of points distributed in a two-dimensional plane, and count the number of points in the set that are inside the circle as M(r). If there are M points in the whole set, one can define the "mass" m(r) in the circle of radius r as:

$$m(r) = \frac{M(r)}{M} \qquad \text{(equation 11)}$$

Consider a set of points lying on a smooth line, or uniformly distributed on a plane. In these two cases, the mass within the circle of radius r will be proportional to r and r^2 respectively. One can then define the mass dimension Dm as the exponent in the following relationship:

$$m(r) \approx r^{D_M} \qquad \text{(equation 12)}$$

In practice, one can measure the mass m(r) in circles of increasing radius starting from the centre of the set and plot the logarithm of m(r) versus the logarithm of r. If the set is fractal, the plot will follow a straight line with a positive slope equal to Dm. As the radius increases beyond the point in the set farthest from the centre of the circle, m(r) will remain constant and the dimension will trivially be zero. This approach is best suited to objects that follow some radial symmetry, such as diffusion-limited aggregates. In the case of points in the plane, it may be best to calculate m(r) as the average mass in a number of circles of radius r.

It can be shown that the mass dimension of a set equals the box dimension. This is true globally, i.e., for the whole set; locally, i.e., in portions of the set, the two dimensions may differ. Let us cover the set with N(d) boxes of size d, and let us define the mass, or probability, in the i-th box mi as:

$$m_i = \frac{M_i}{M} \qquad \text{(equation 13)}$$

Mi is the number of points in the i-th box and M is the total number of points in the set. We can now write the average mass, or probability, in boxes of size d as m(d), the average mi in the N(d) boxes:

$$m(d) = \frac{1}{N(d)} \sum_{i=1}^{N(d)} m_i = \frac{1}{N(d)} \qquad \text{(equation 14)}$$

(the sum of all the masses mi is obviously one). As the operation of calculating the mass contained in a box of size d is the same as calculating the mass in a circle of radius r, we can write our definition of mass dimension (12) in terms of d rather than r:

$$m(d) \approx d^{D_M} \qquad \text{(equation 15)}$$

By using (4) and re-arranging terms, we obtain:

$$N(d) \approx \frac{1}{d^{D_M}} \qquad \text{(equation 16)}$$

This is the definition of the box dimension; thus, the mass dimension equals the box dimension.

B.5 Ruler Dimension

Consider the problem of estimating the fractal dimension of a jagged, self-similar line, the typical example being a coastline. Define N(d) as the number of steps taken by walking a divider (ruler) of length d on the line, the ruler dimension Dr is defined as:

$$N(d) \approx d^{-Dr} \qquad \text{(equation 17)}$$

The basis of this method is as follows: if the line is Euclidean, Dr = 1, then the length of the line will be a constant independent of d. Note that this is bound to be true for values of d sufficiently small. For example, the perimeter of a circle measured by a ruler of length d will be constant when d is much less than the radius of the circle. At the other extreme, if the line completely fills space, Dr = 2, i.e., the length of the line is linearly related to the length of the ruler. This can be shown to be true by equating the measured length of the line N(d) with the number of boxes needed to cover the line N(d) times d: When Dr = 2, the number of filled boxes is proportional to 1/d^2, and the line fills the two-dimensional space. One can show the formal equivalence of the ruler and box dimension.

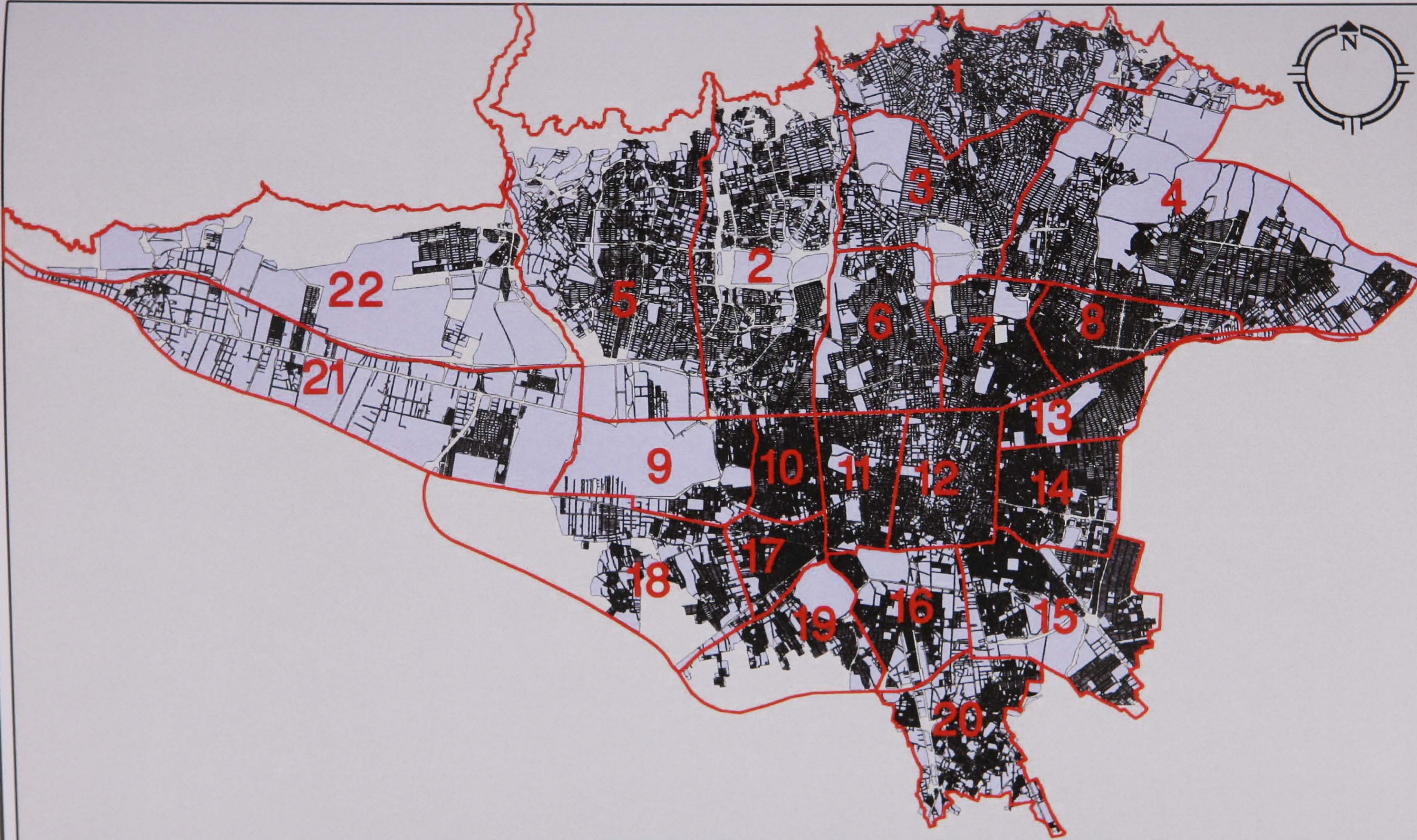
In practice, to obtain Dr one counts the number of steps N(d) taken by walking a divider (ruler) of length d on the line, and plot the logarithm of N(d) versus the logarithm of d. If the line is indeed fractal, this plot will follow a straight line with a negative slope that equals -Dr. It should be noted that in general, a ruler of length d will not cover exactly the line, but we will be left with a remainder. Benoit keeps this remainder and therefore has non-integer values of N(d).

APPENDIX C

THE LOGARITHMIC GRAPHS

OF

THE 22 DISTRICTS OF TEHRAN



The Official Boundaries of the 22 Districts of Tehran

The Logarithmic Graphs of the 22 Districts of Tehran

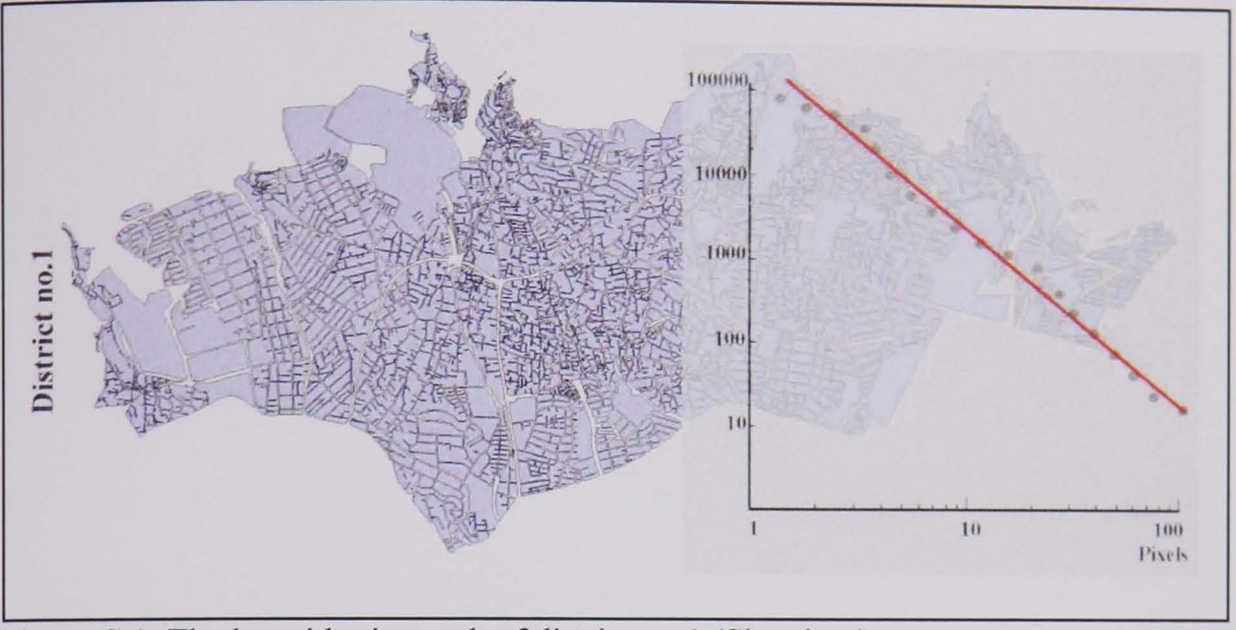


Figure C.1: The logarithmic graph of district no.1 (Shemiran).

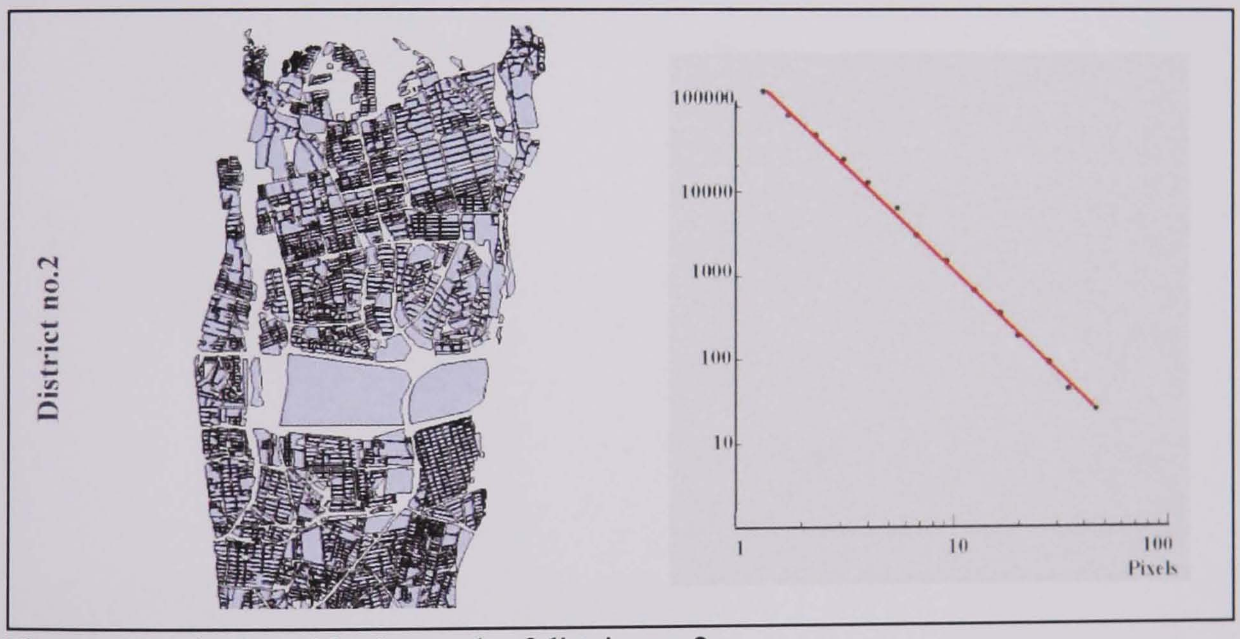


Figure C.2: The logarithmic graph of district no.2.

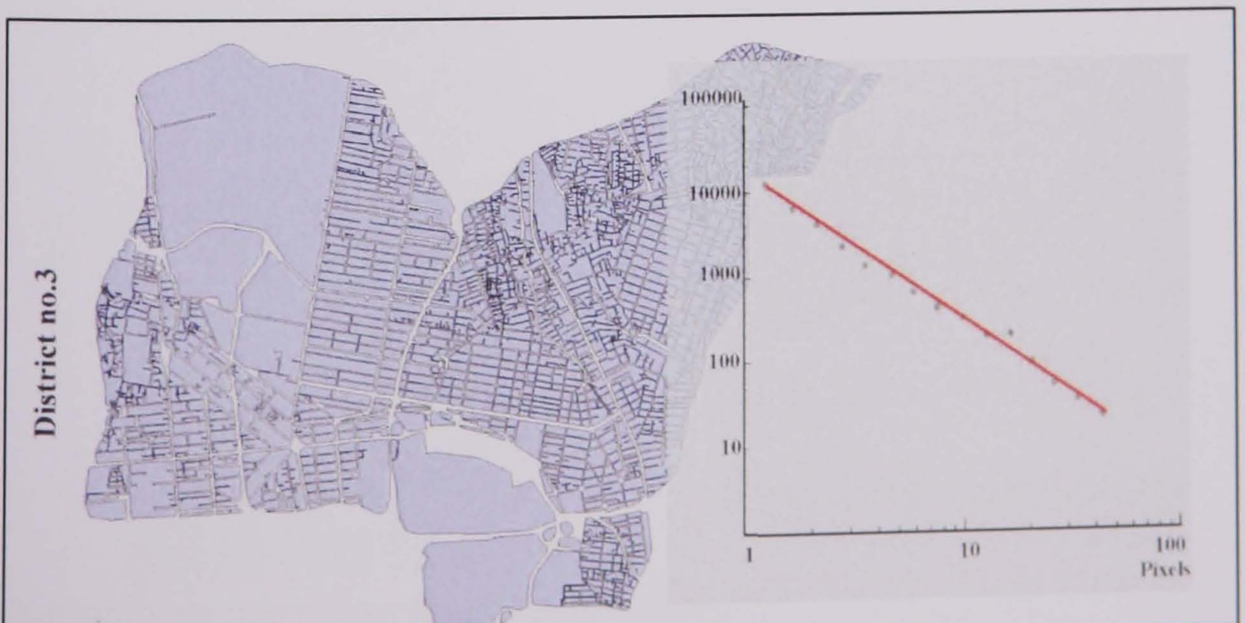


Figure C.3: The logarithmic graph of district no.3.

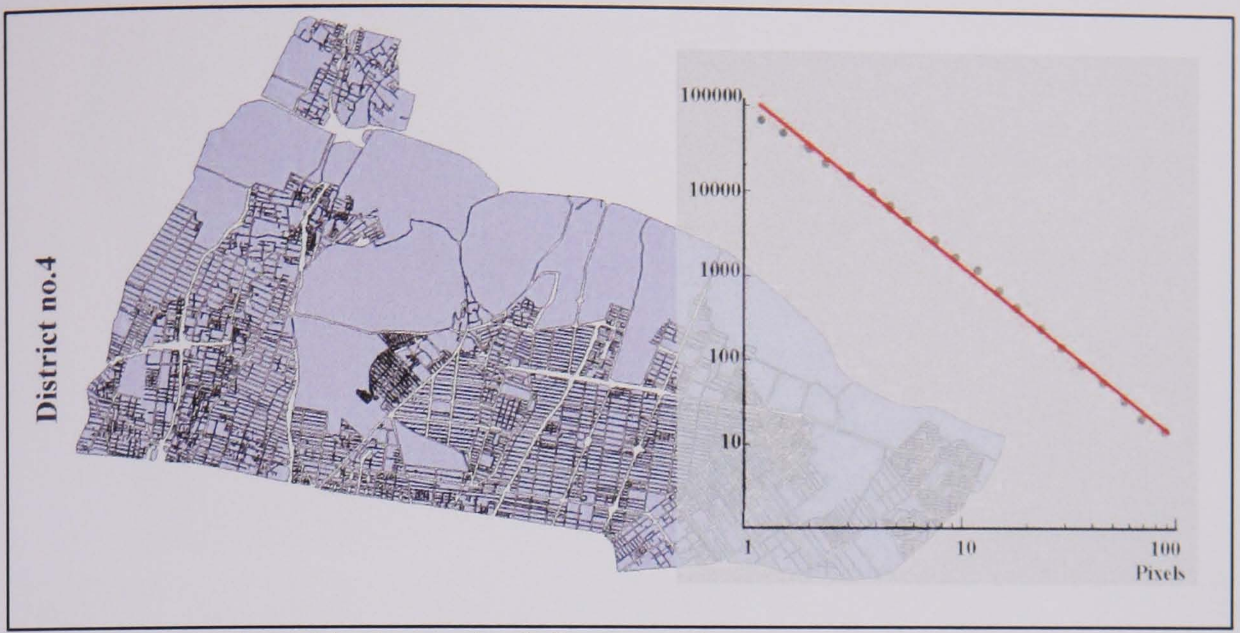


Figure C.4: The logarithmic graph of district no.4.

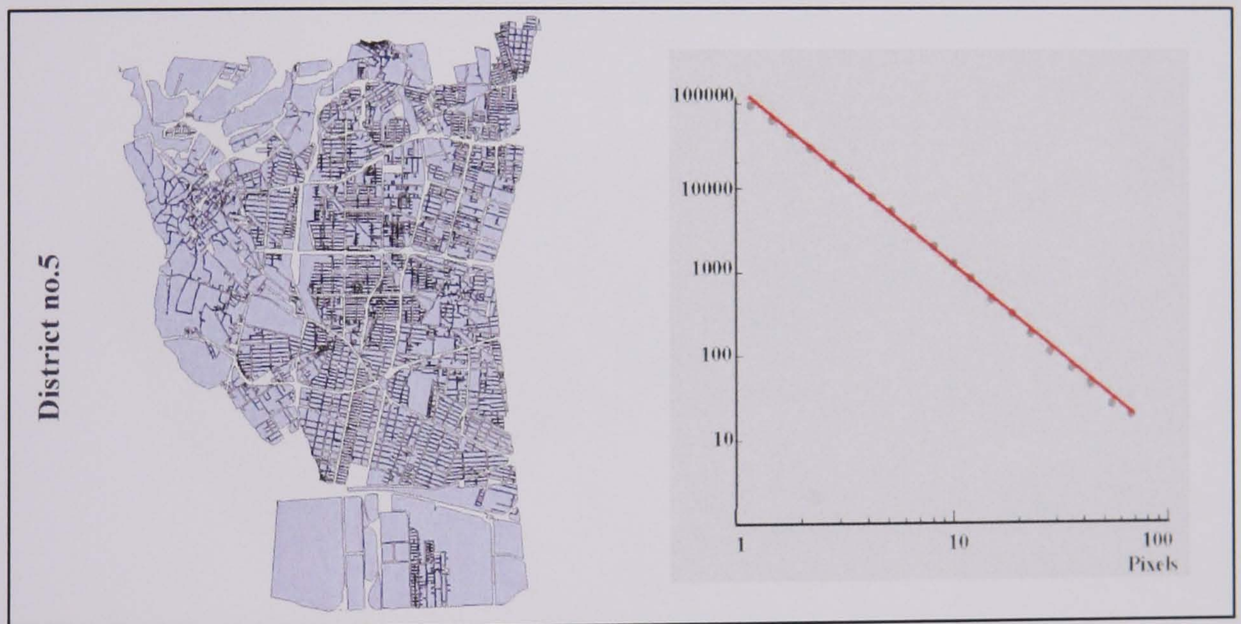


Figure C.5: The logarithmic graph of district no.5.

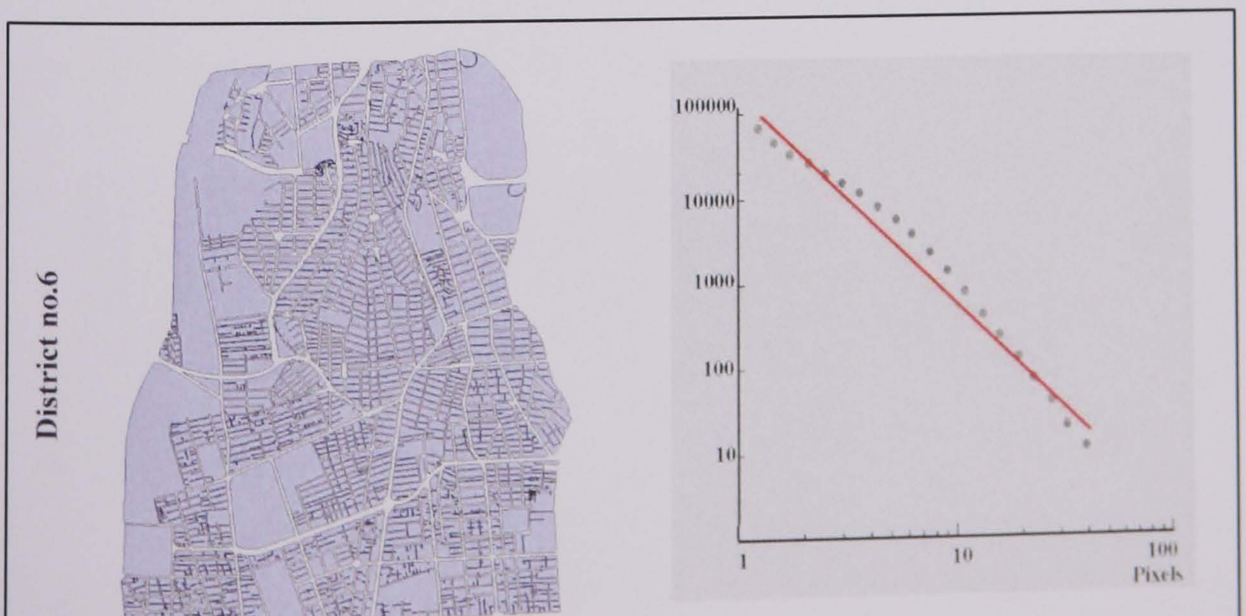


Figure C.6: The logarithmic graph of district no.6.

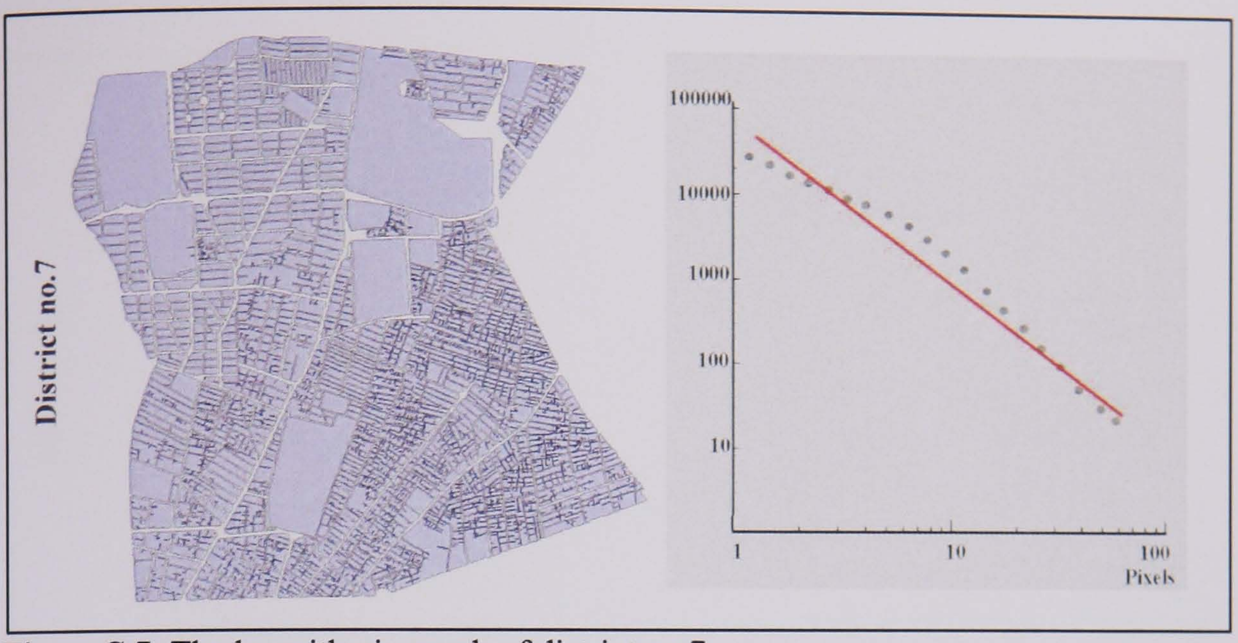


Figure C.7: The logarithmic graph of district no.7.

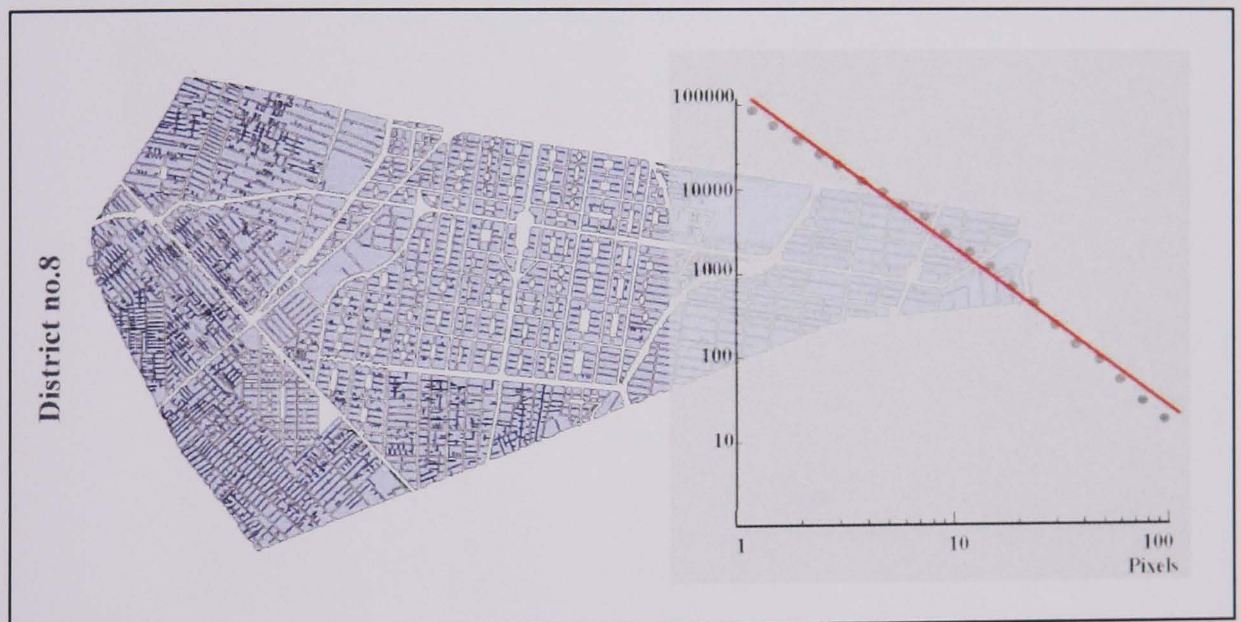


Figure C.8: The logarithmic graph of district no.8.

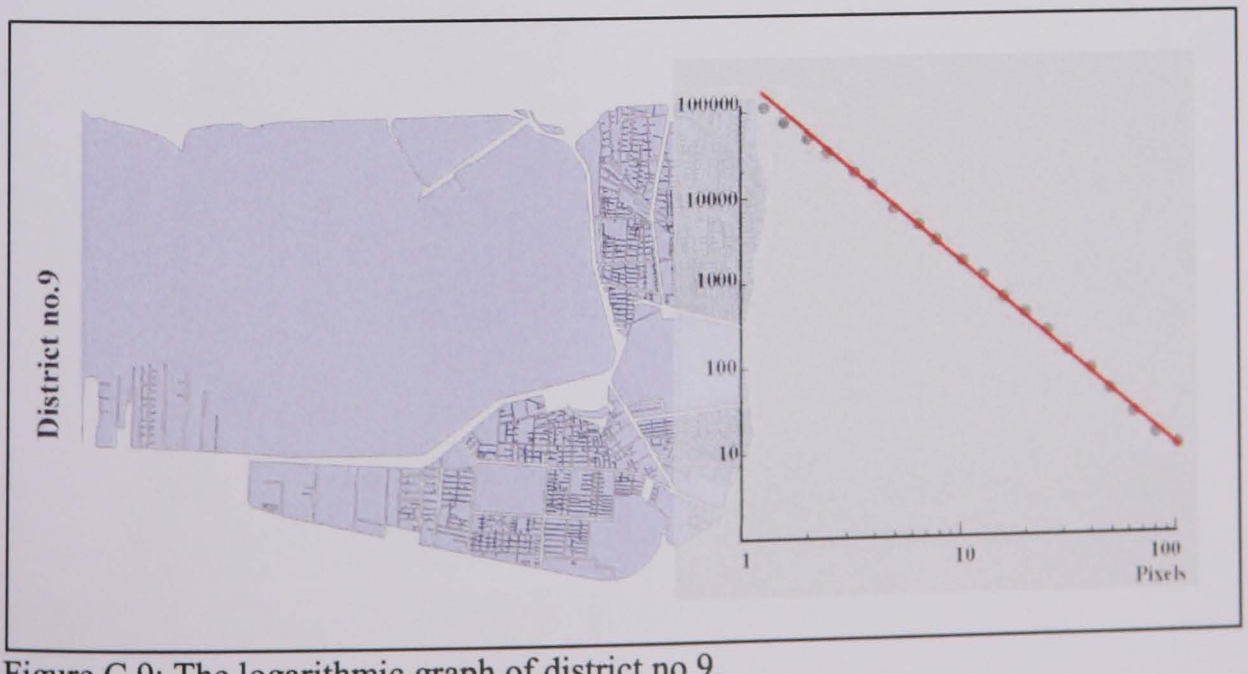


Figure C.9: The logarithmic graph of district no.9.

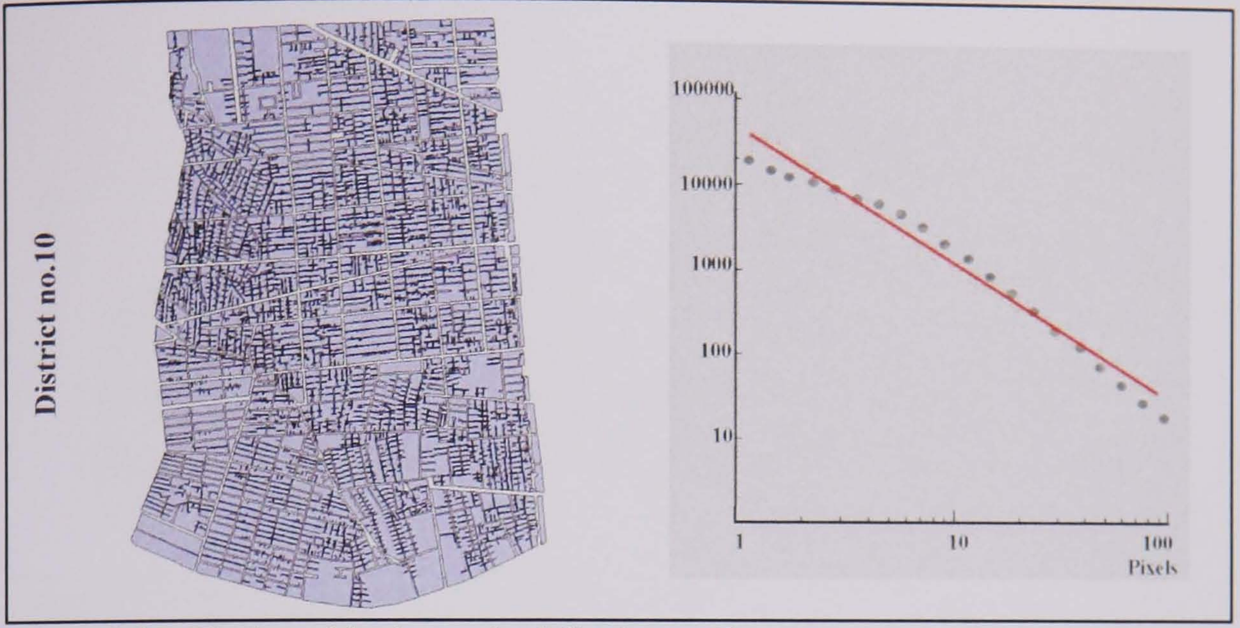


Figure C.10: The logarithmic graph of district no.10.

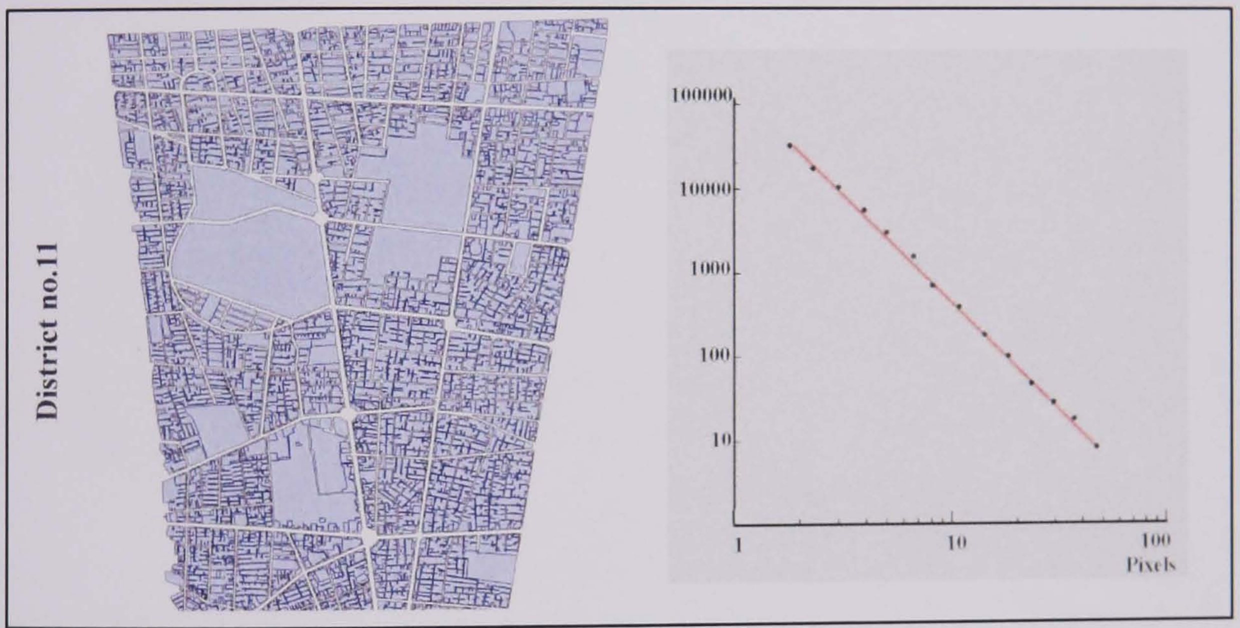


Figure C.11: The logarithmic graph of district no11.

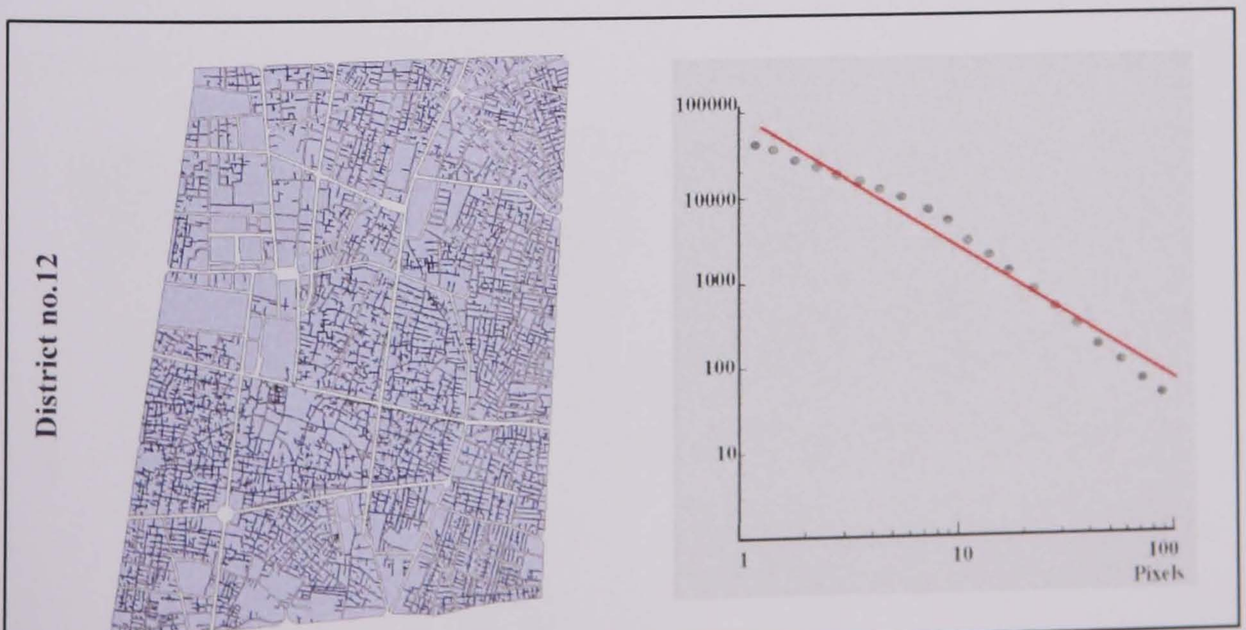


Figure C.12: The logarithmic graph of district no12.

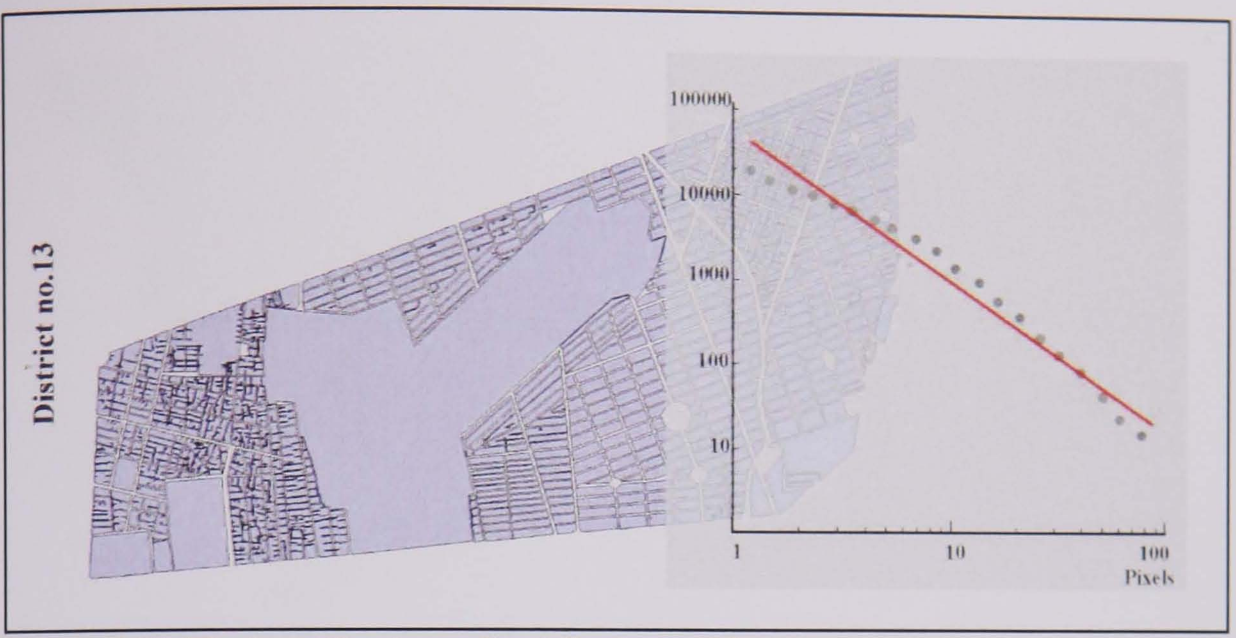


Figure C.13: The logarithmic graph of district no.13.

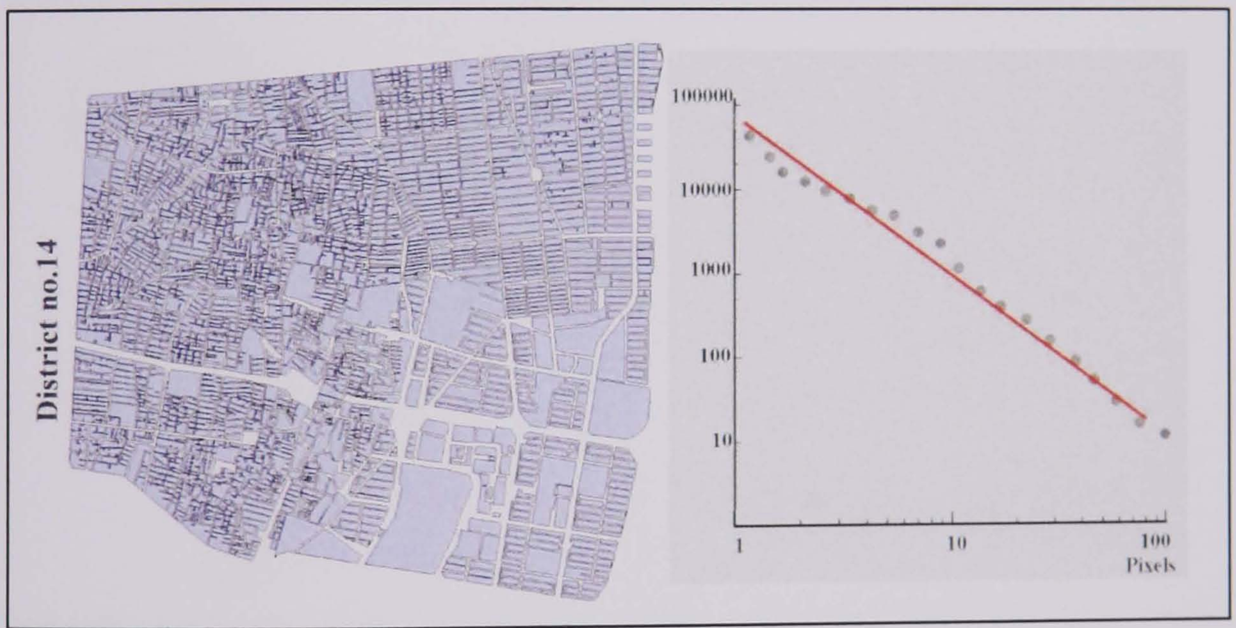


Figure C.14: The logarithmic graph of district no14.

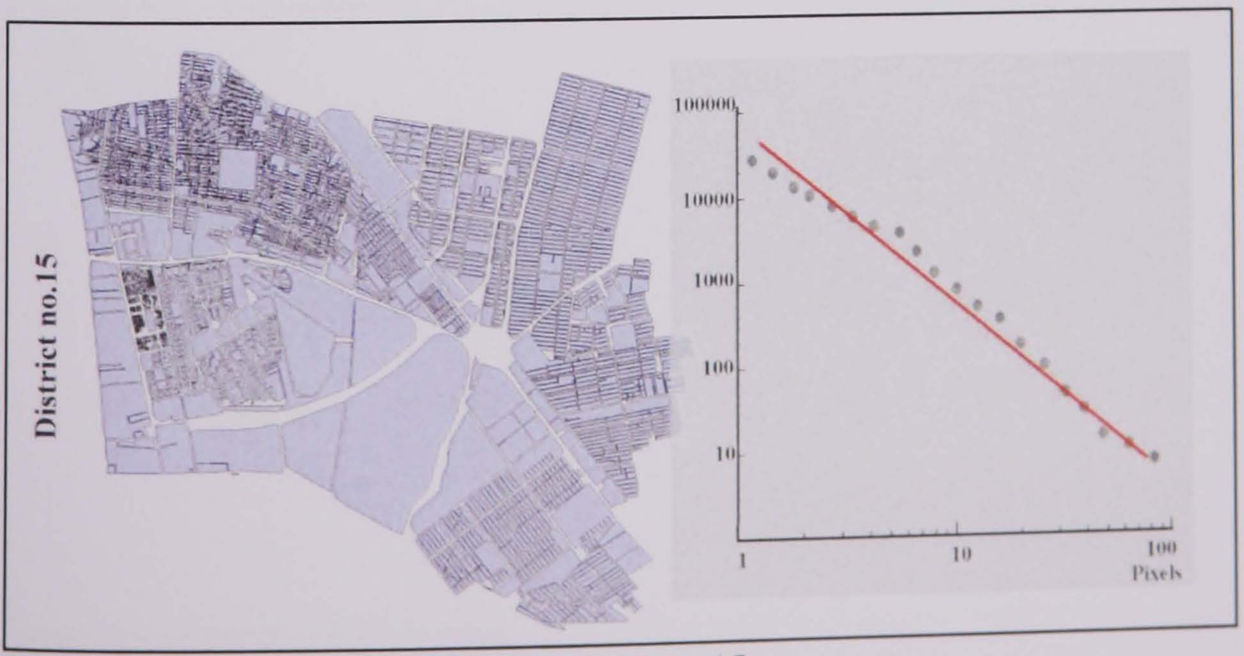


Figure C.15: The logarithmic graph of district no.15.

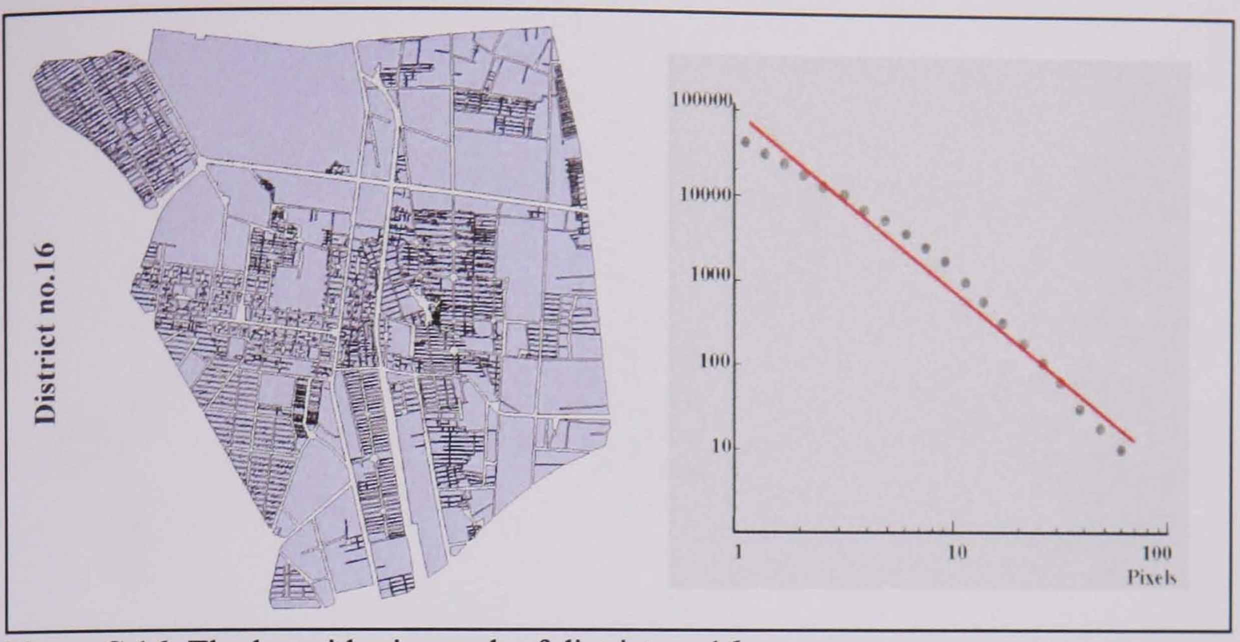


Figure C.16: The logarithmic graph of district no.16.

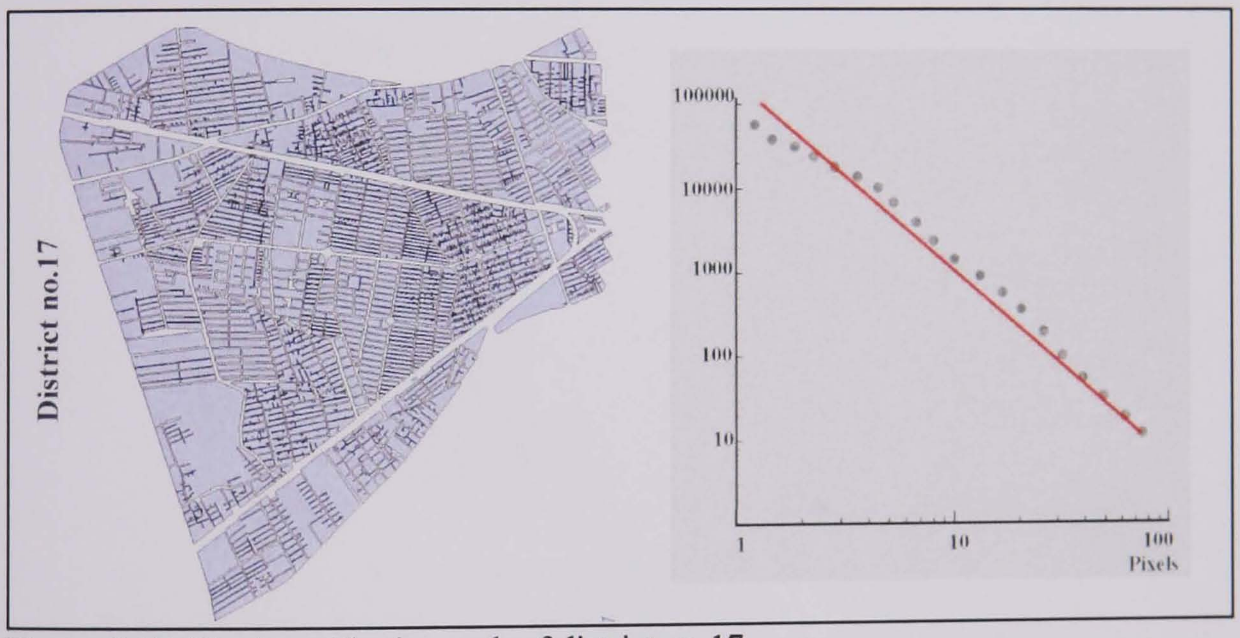


Figure C.17: The logarithmic graph of district no.17.

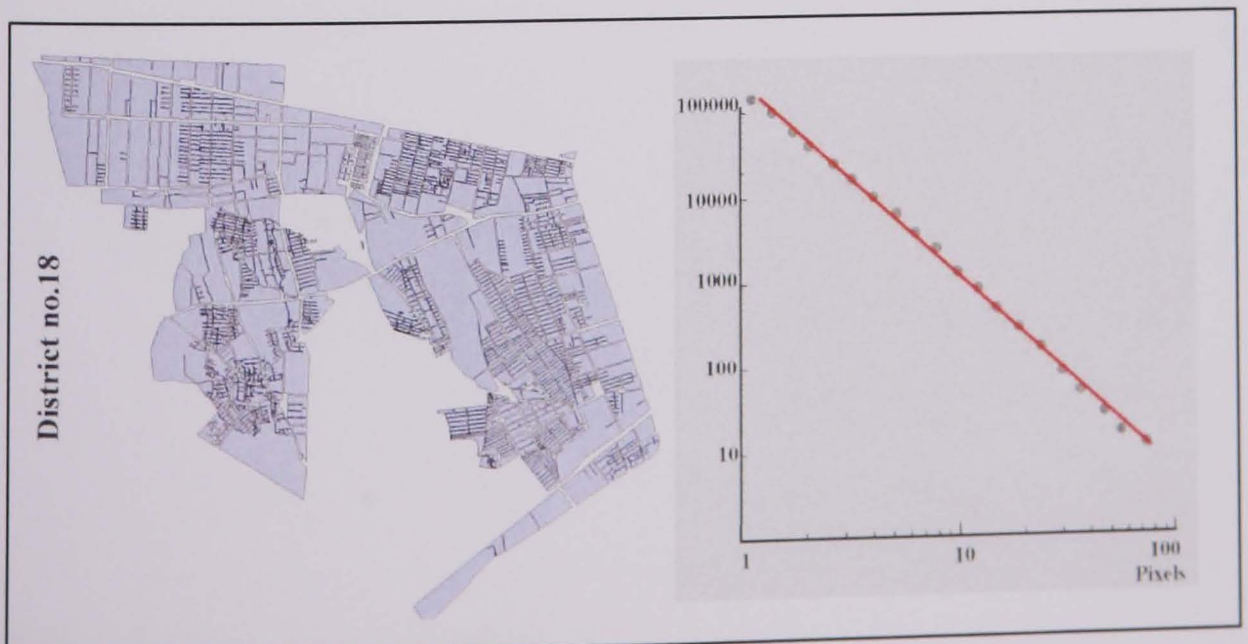


Figure C.12: The logarithmic graph of district no.18.

Figure C.19: The logarithmic graph of district no.19.

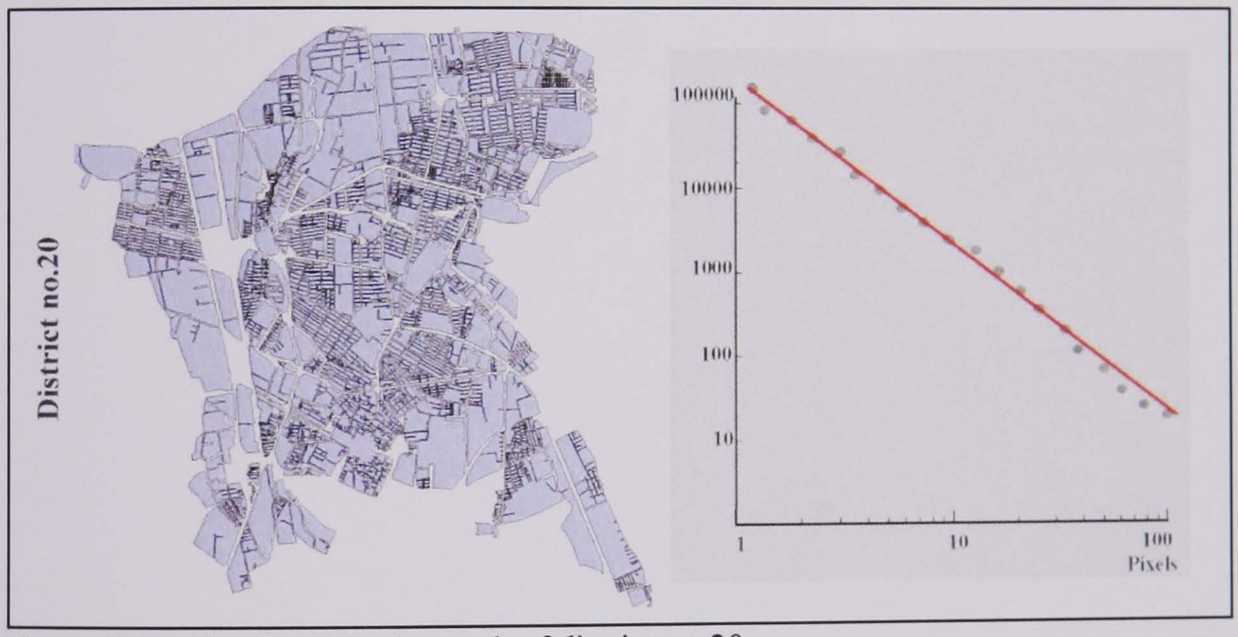


Figure C.20: The logarithmic graph of district no.20.

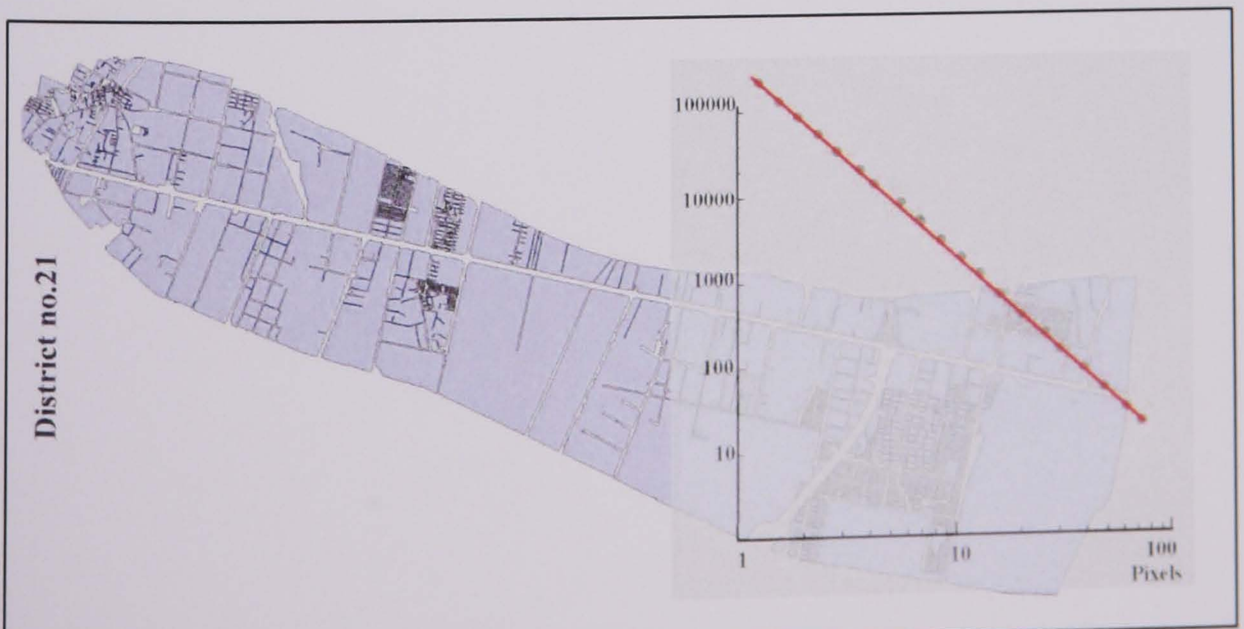


Figure C.21: The logarithmic graph of district no.21.

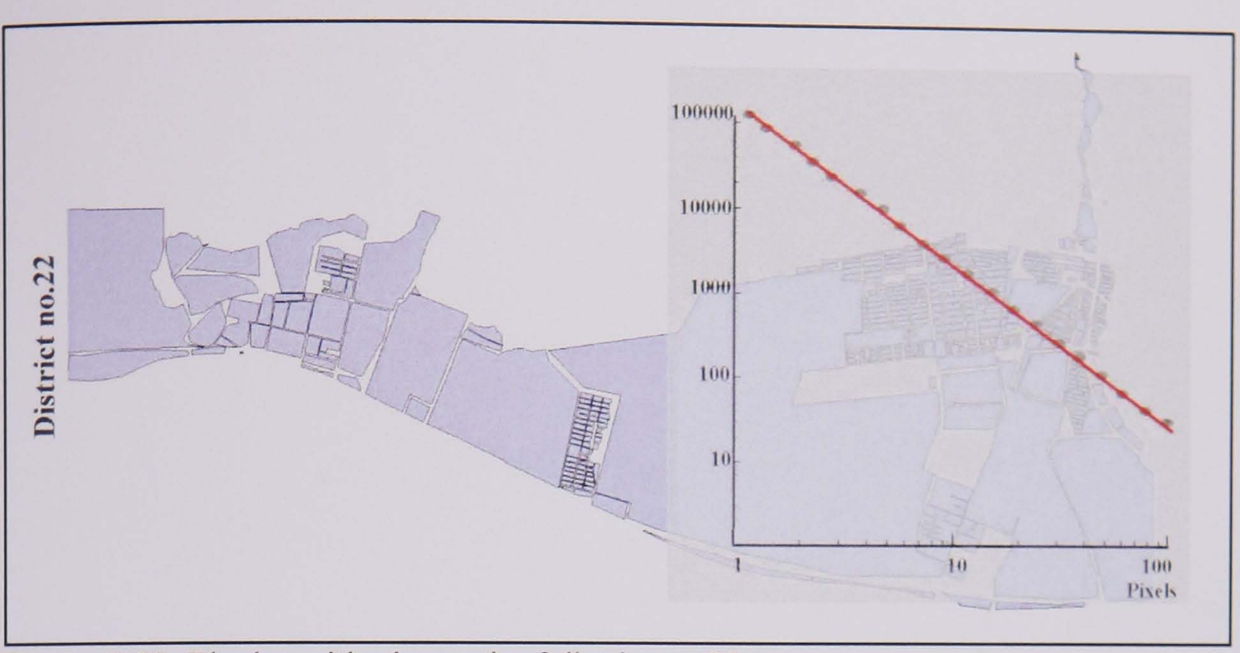
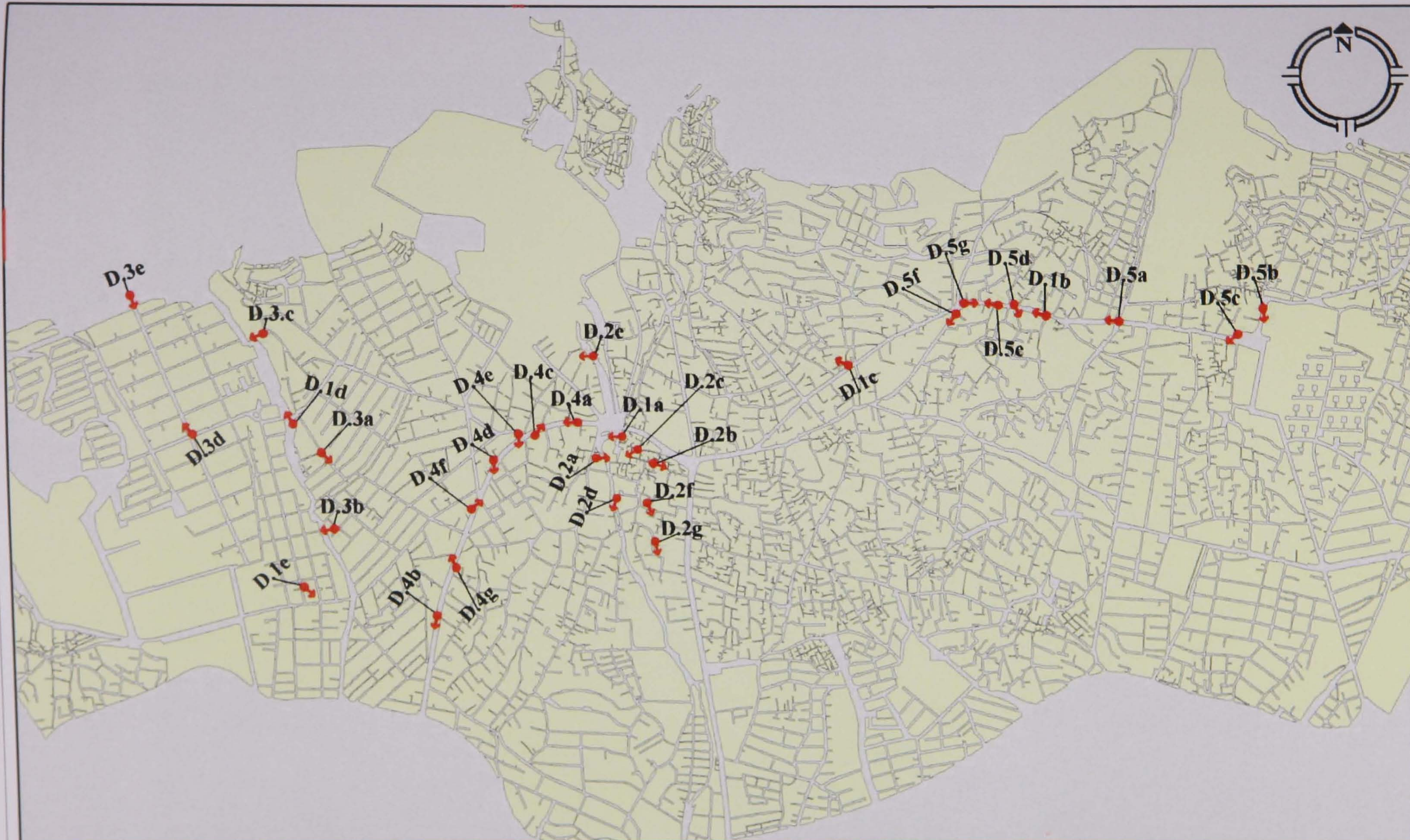


Figure C.22: The logarithmic graph of district no.22.

APPENDIX D

IMAGES OF SHEMIRAN



A Guide for the Photos Taken in Shemiran

High-rise buildings in Shemiran

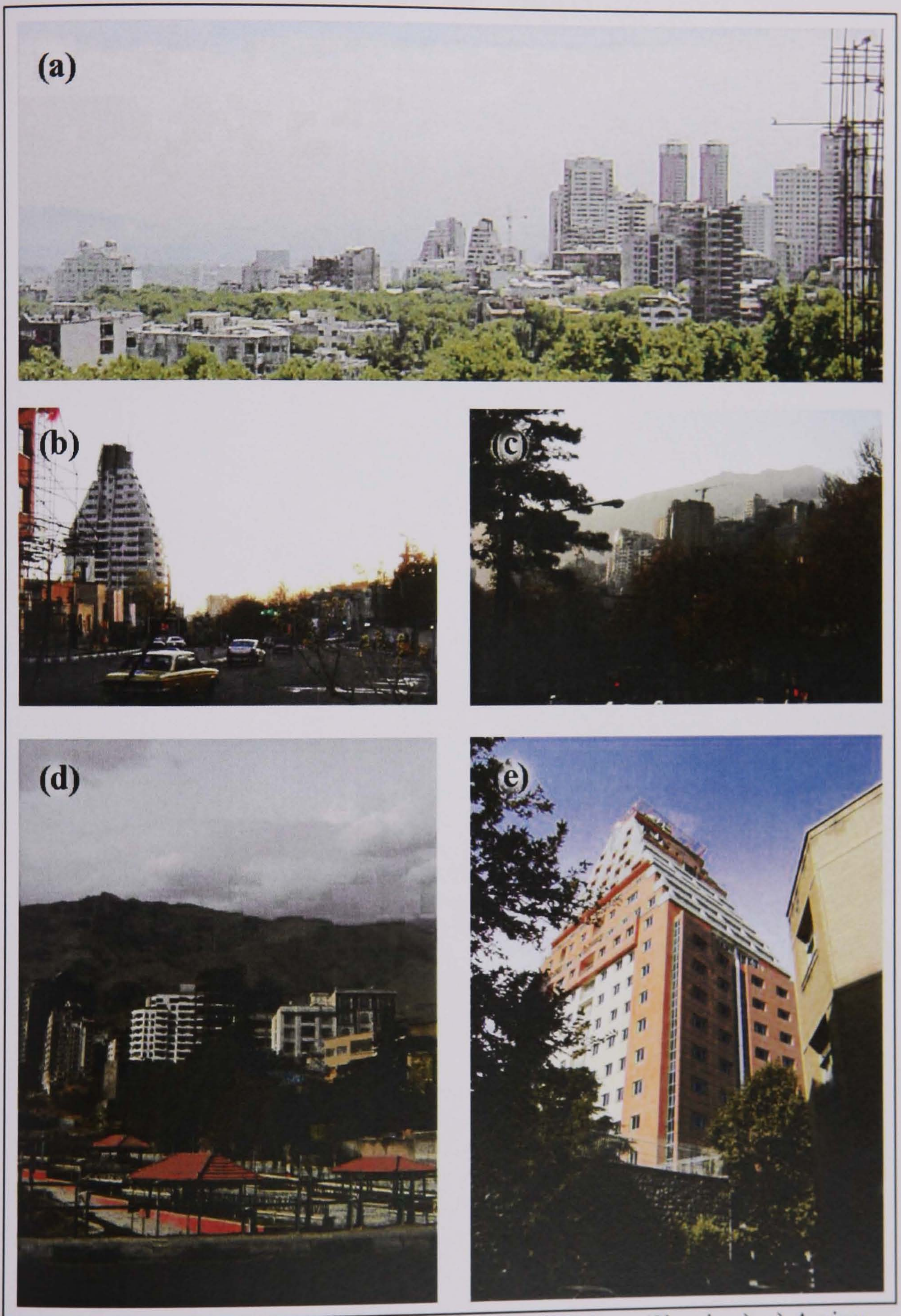


Figure D.1: Emergent high-rise buildings in northern Tehran (Shemiran). a) A view from *Bazarche Ghaem*, Tajrish Square, to west Shemiran. b and c) Views from Niavaran Street to west Shemiran. d) A view from Sasan Boulevard to Velenjak. e) A residential complex in Velenjak. (Photos taken by the author, July 2008)

Images of Tajrish

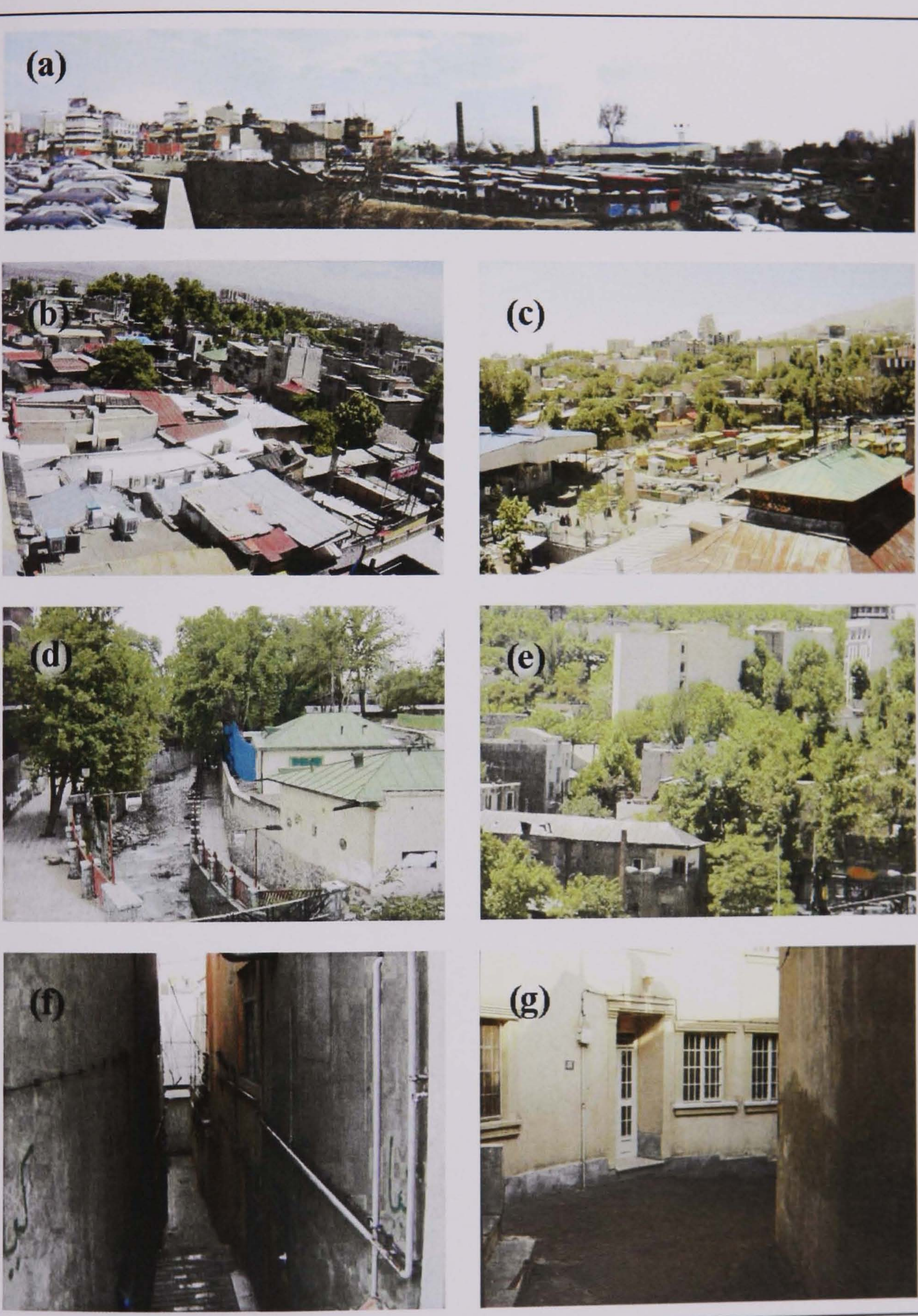


Figure D.2: Views of Tajrish. a) A panorama of southern Tajrish square including the car park, bus terminal and the Shrine of *Imamzadeh Saleh*. b) A view from *Bazarcheh Ghaem* to neighbourhood T-N15. c) A view from *Tekieh Bala* to western Shemiran. d) A view of neighbourhood T-N14. e) A view of neighbourhood T-N1. f and g) Two old alleys with contemporary houses in Tajrish. (Photos taken by the author, July 2008, April 2009)

Images of Velenjak

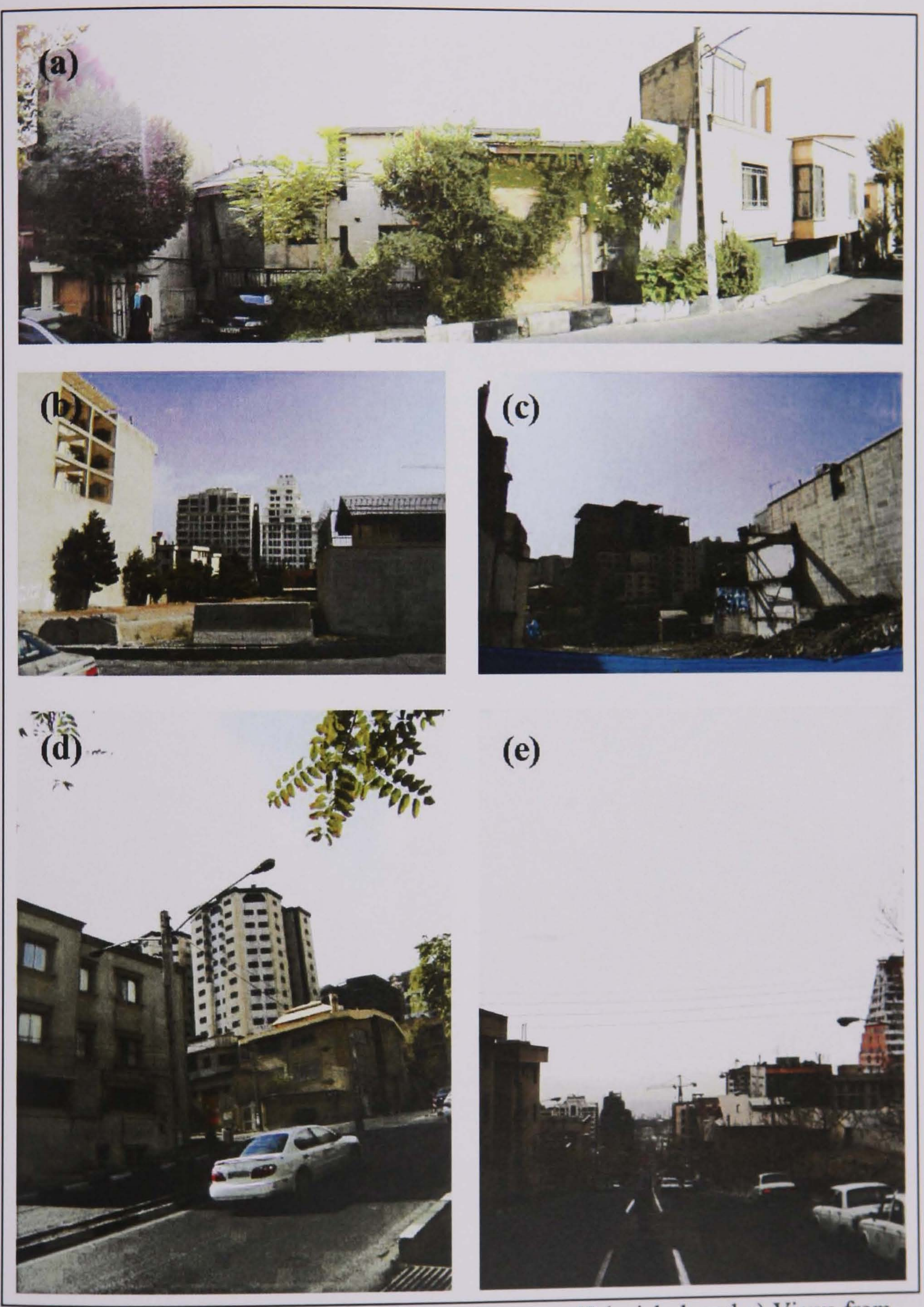


Figure D.3: a) A panorama of typical houses in eastern Velenjak. b and c) Views from east to west Velenjak demonstrating a transition from two-stories houses to high-rise apartments creating a contradictory composition. Views from south to north (d) and north to south (e), the main street in Velenjak. (Photos taken by the author, July 2008, April 2009)

Images of Vali-e Asr Street

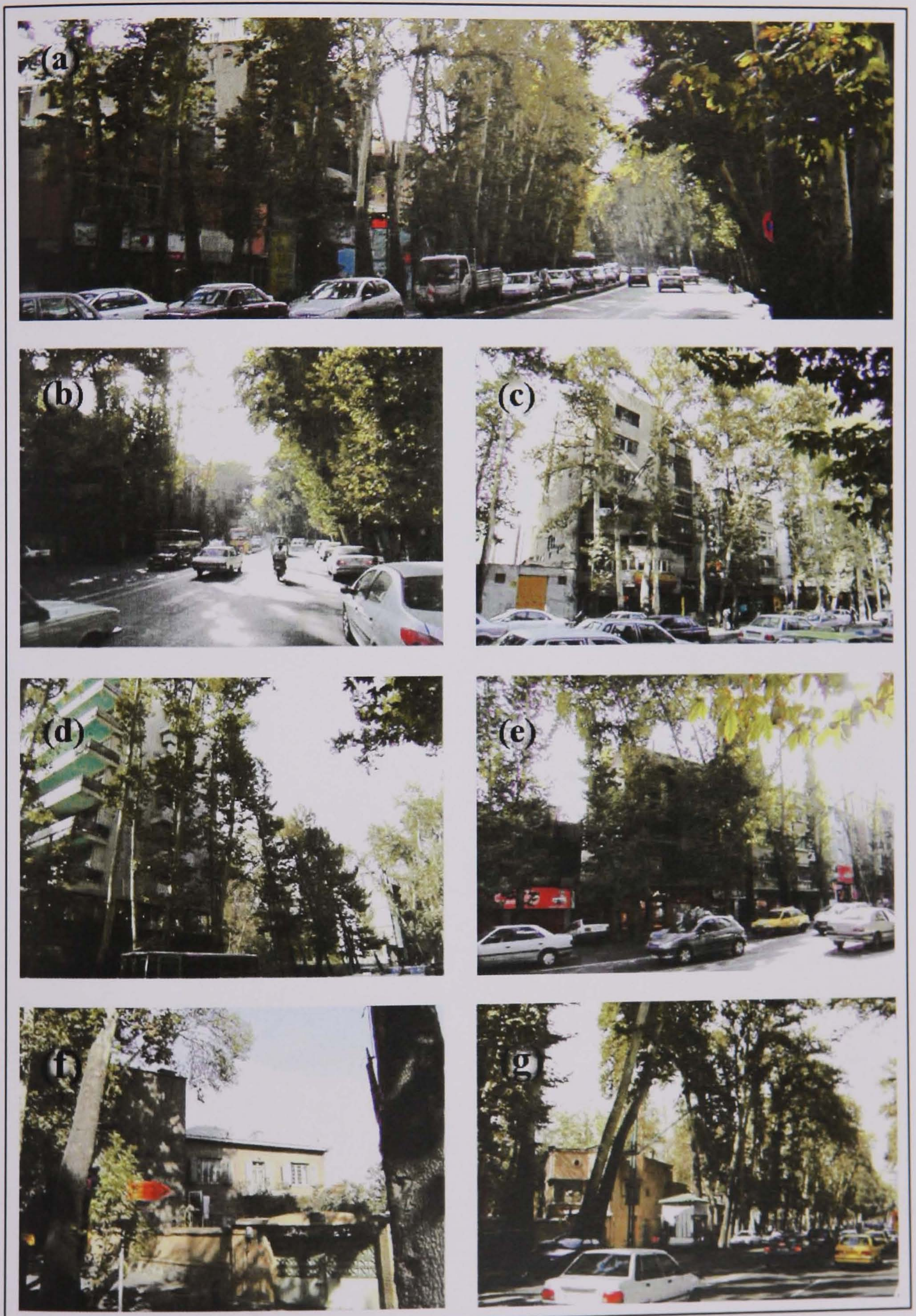


Figure D.4: Diverse building types and styles behind the old trees of Vali-e Asr Street. (Photos taken by the author, July 2008, April 2009)

Images of Niavaran Street

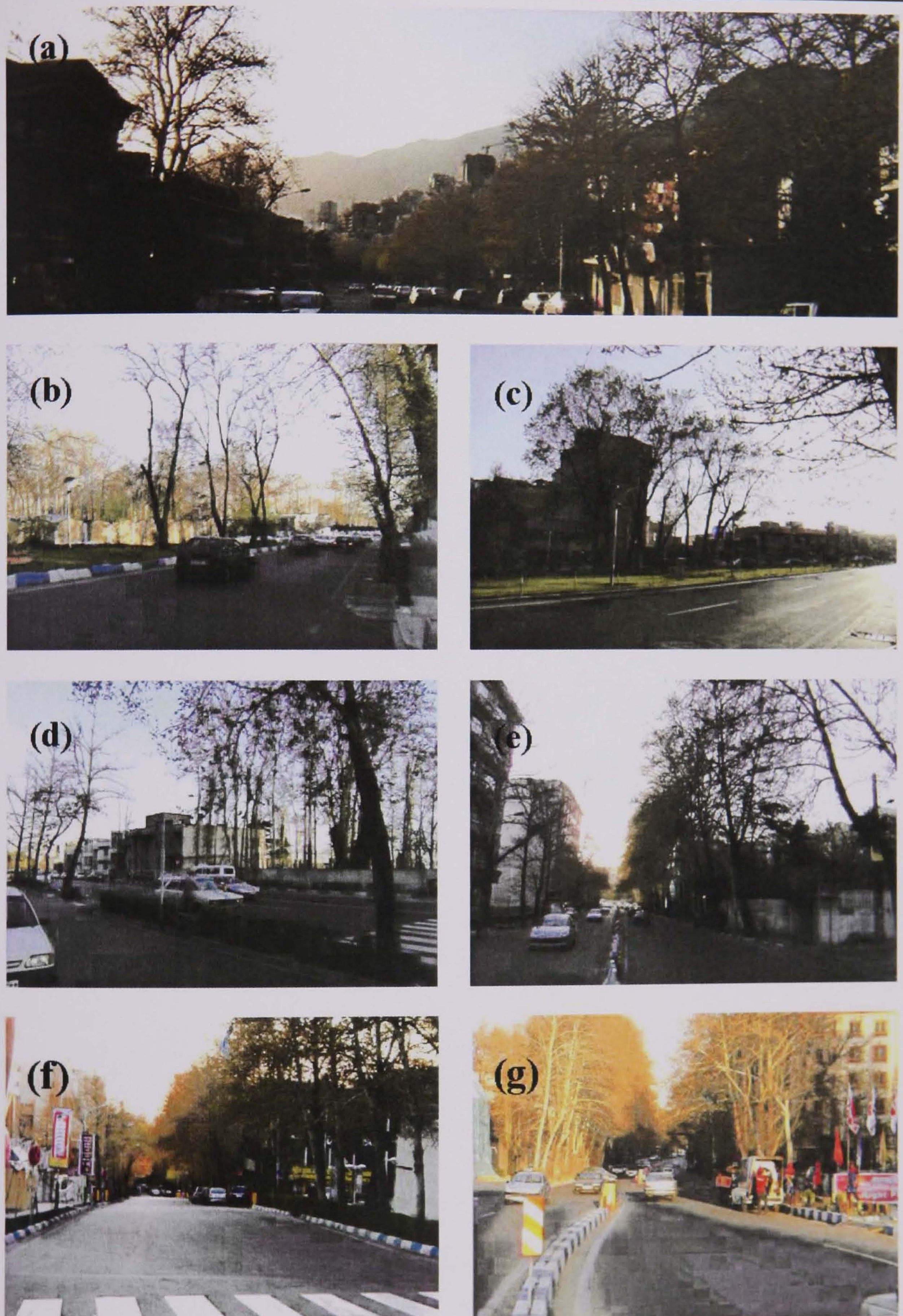


Figure D.5: Niavaran Street. a) East to west view. b and c) views of Niavaran Square. d and e) Views from the street side to remaining gardens in Niavaran. g) West to east view. (Photos taken by the author, July 2008, April 2009)

APPENDIX E

THE AERIAL PHOTOS OF TAJRISH
FROM 1956 TO 2002

1956

Figure E.1: The aerial photo of Tajrish in 1956 (TGIC Library, Tehran Geographic Information Centre).

1965

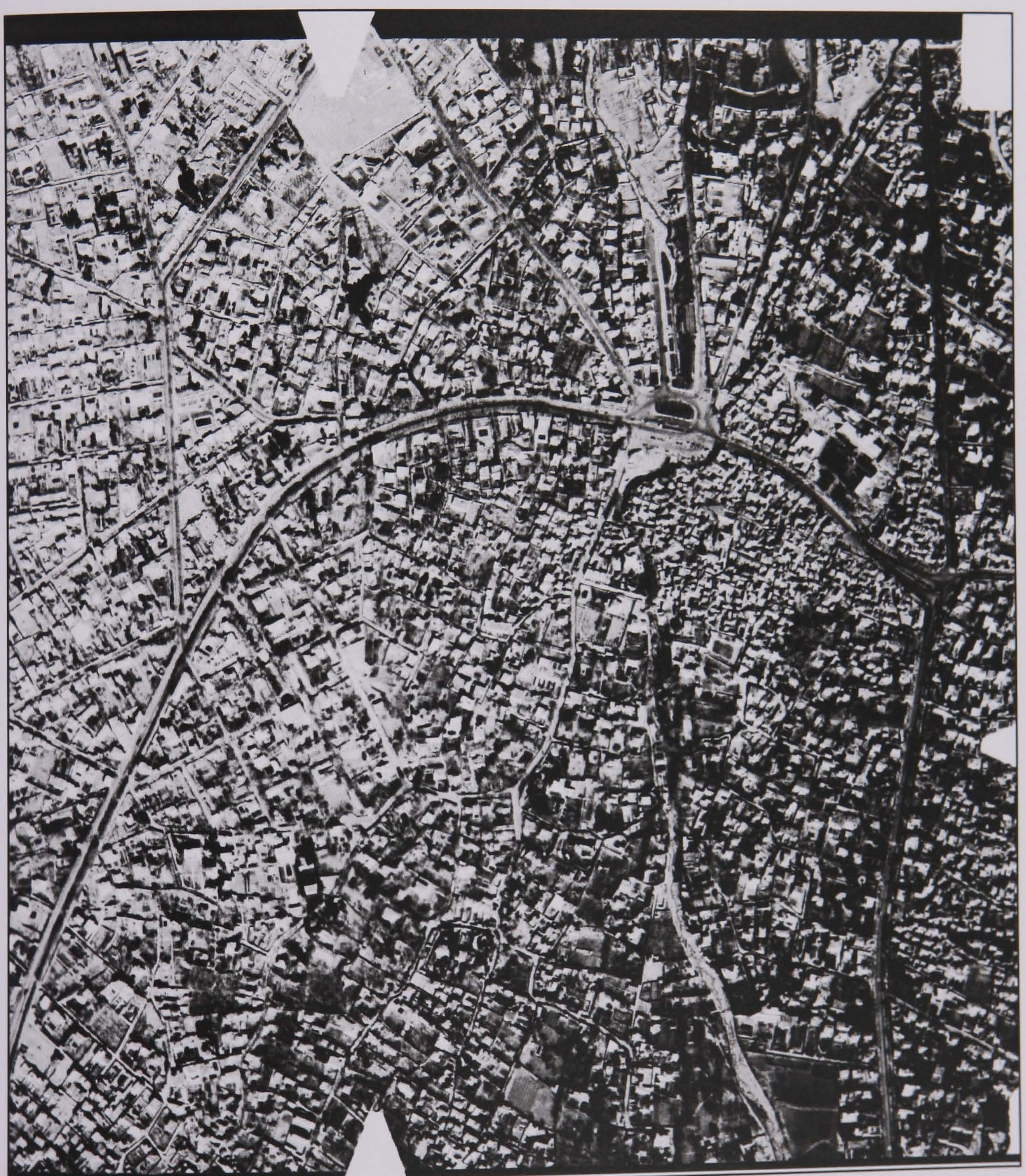


Figure E.2: The aerial photo of Tajrish in 1965 (TGIC Library, Tehran Geographic Information Centre).

1969

Figure E.3: The aerial photo of Tajrish in 1969 (TGIC Library, Tehran Geographic Information Centre).

1979

Figure E.4: The aerial photo of Tajrish in 1979 (TGIC Library, Tehran Geographic Information Centre).

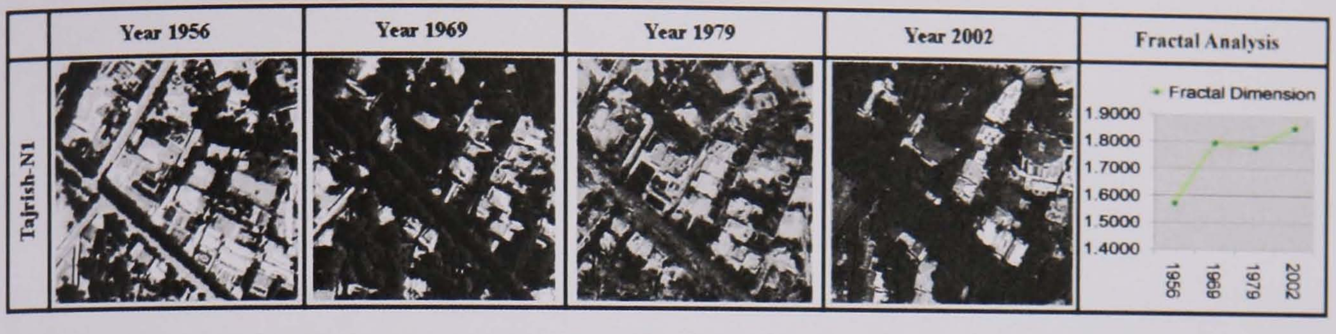
2002

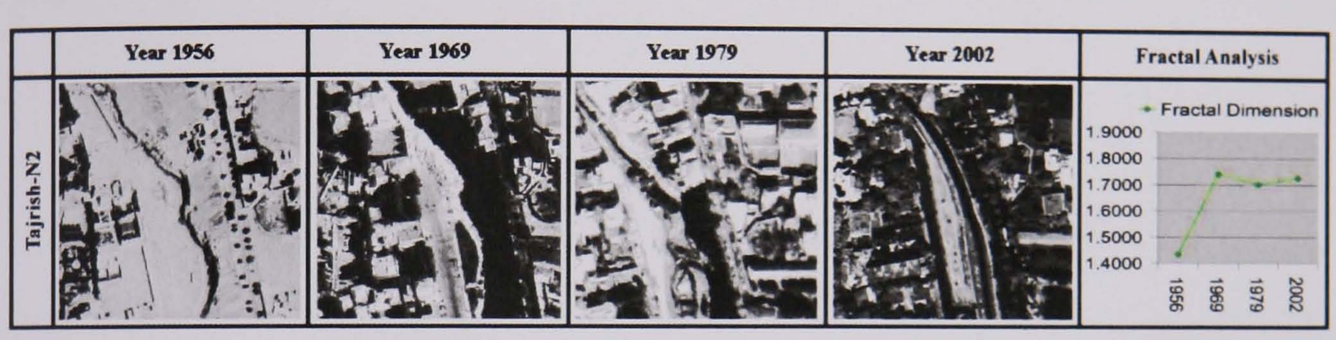
Figure E.5: The aerial photo of Tajrish in 2002 (TGIC Library, Tehran Geographic Information Centre).

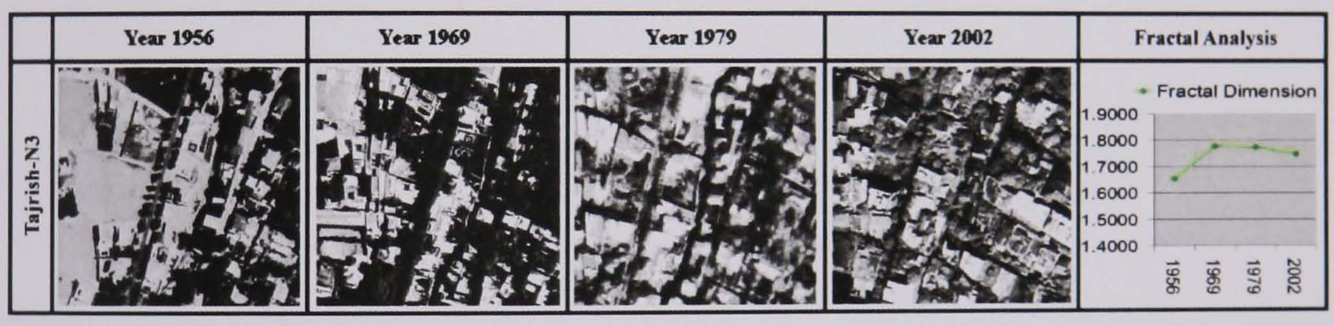
APPENDIX F

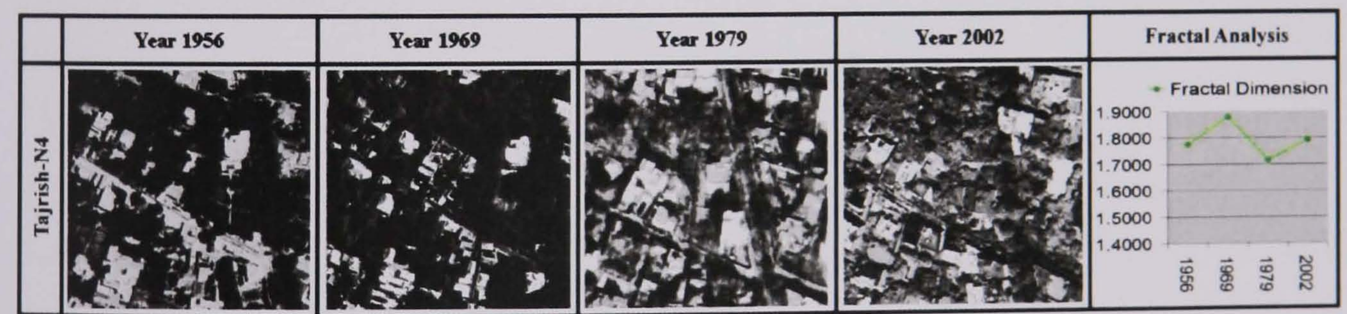
THE FRACTAL ANALYSIS CHARTS
OF
24 NEIGHBOURHOODS IN TAJRISH

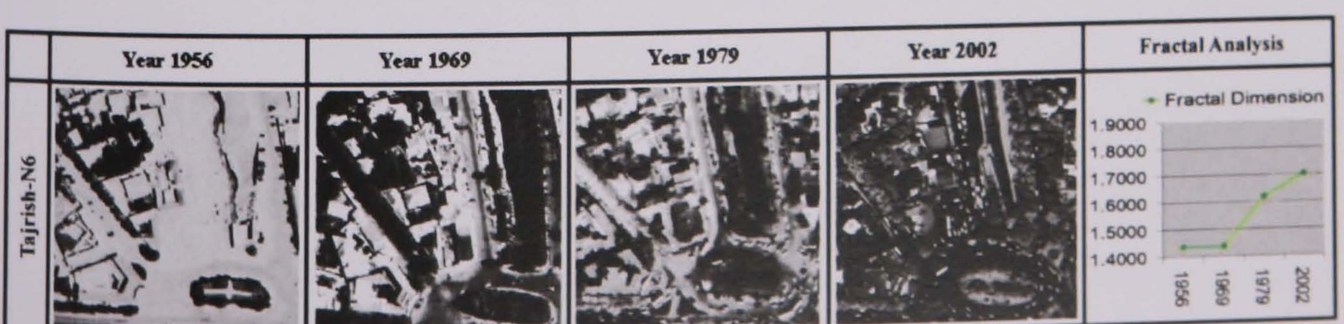
The Fractal Analysis Charts of 24 neighbourhoods in Tajrish from 1956 to 2002

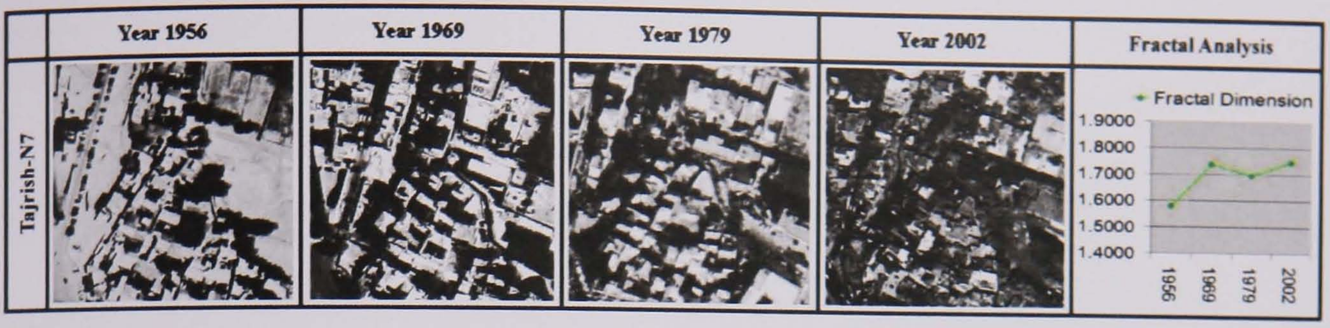


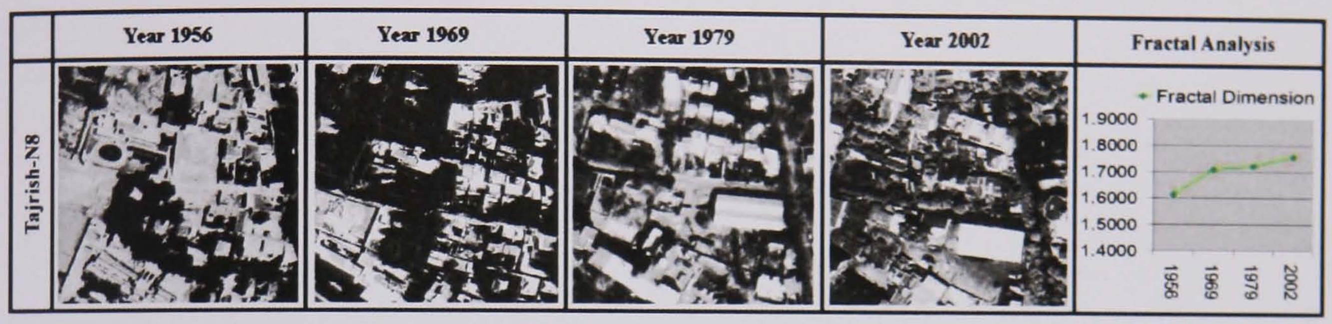









Tajrish-N7
Year 1956
Year 1969
Year 1979
Year 2002
Fractal Analysis
Fractal Dimension
1.9000
1.8000
1.7000
1.6000
1.5000
1.4000
1956
1969
1979
2002


Tajrish-N8
Year 1956
Year 1969
Year 1979
Year 2002
Fractal Analysis
Fractal Dimension
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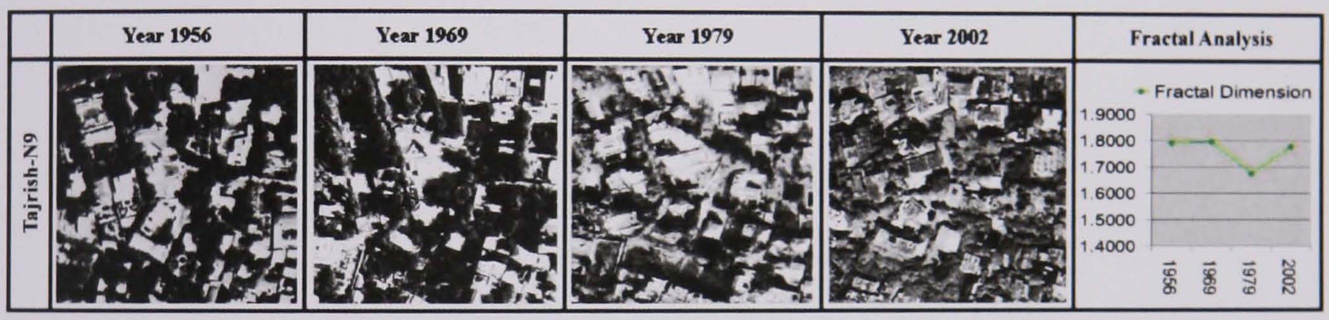
1.8000
1.7000
1.6000
1.5000
1.4000
1956
1969
1979
2002


Tajrish-N9
Year 1956
Year 1969
Year 1979
Year 2002
Fractal Analysis
Fractal Dimension
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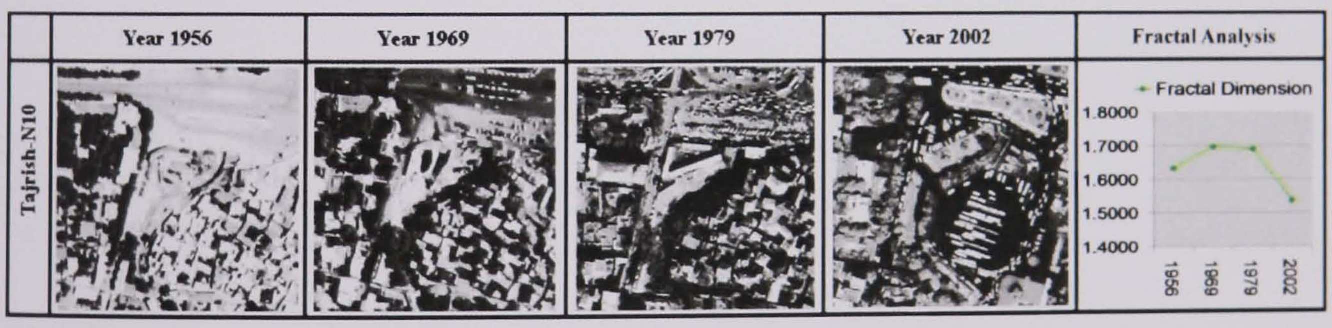
1.8000
1.7000
1.6000
1.5000
1.4000
1956
1969
1979
2002


Tajrish-N10
Year 1956
Year 1969
Year 1979
Year 2002
Fractal Analysis
Fractal Dimension
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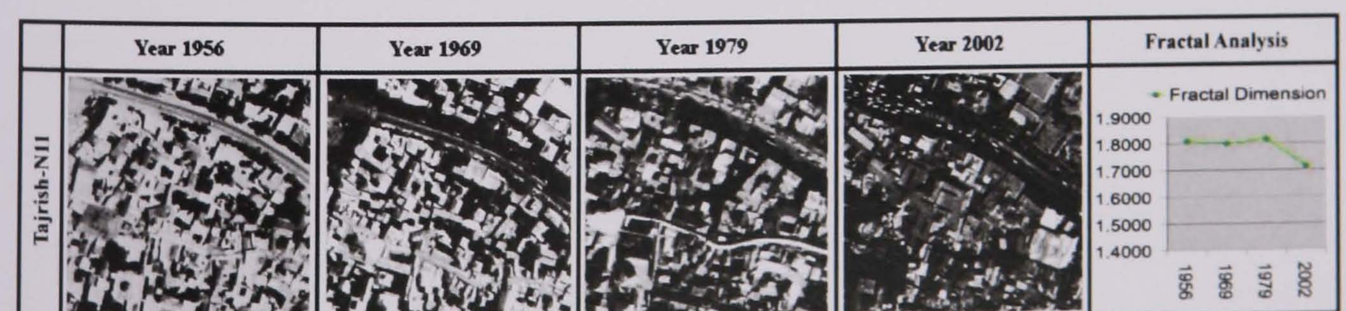
1.7000
1.6000
1.5000
1.4000
1956
1969
1979
2002


Tajrish-N11
Year 1956
Year 1969
Year 1979
Year 2002
Fractal Analysis
Fractal Dimension
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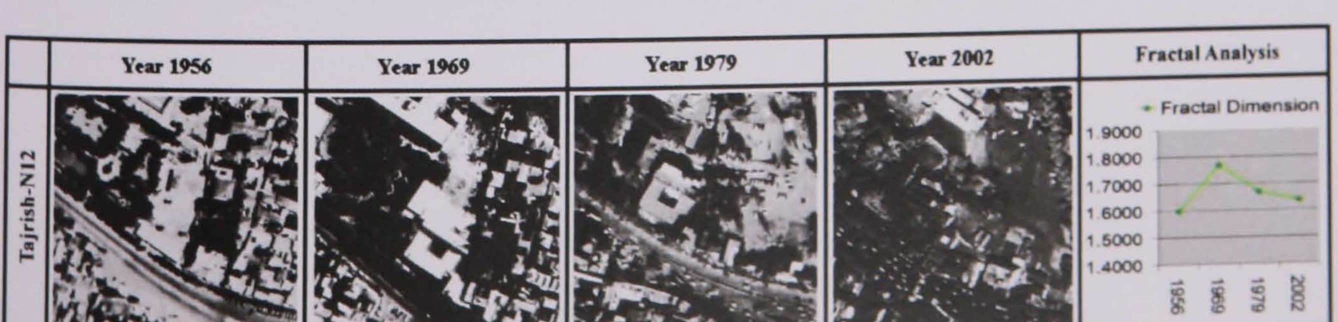
1.8000
1.7000
1.6000
1.5000
1.4000
1956
1969
1979
2002


Tajrish-N12
Year 1956
Year 1969
Year 1979
Year 2002
Fractal Analysis
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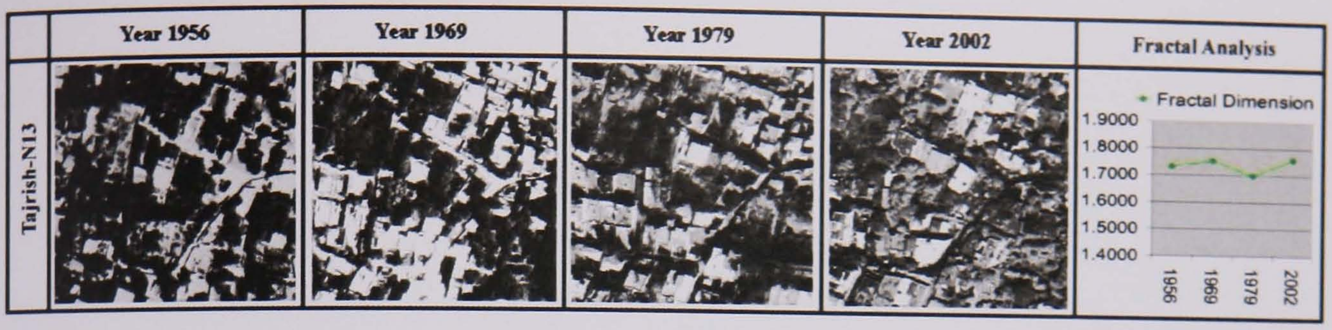
1.6000
1.5000
1.4000
1956
1969
1979
2002


Tajrish-N13
Year 1956
Year 1969
Year 1979
Year 2002
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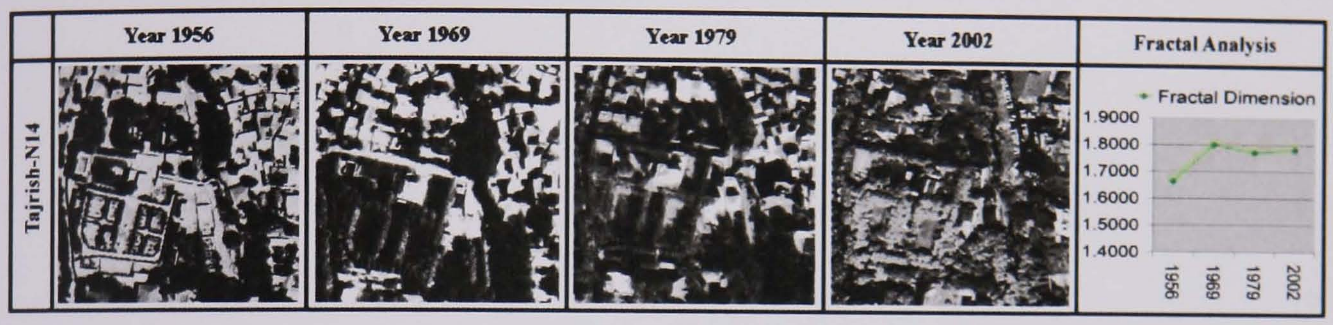
1.7000
1.6000
1.5000
1.4000
1956
1969
1979
2002


Tajrish-N14
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Year 1969
Year 1979
Year 2002
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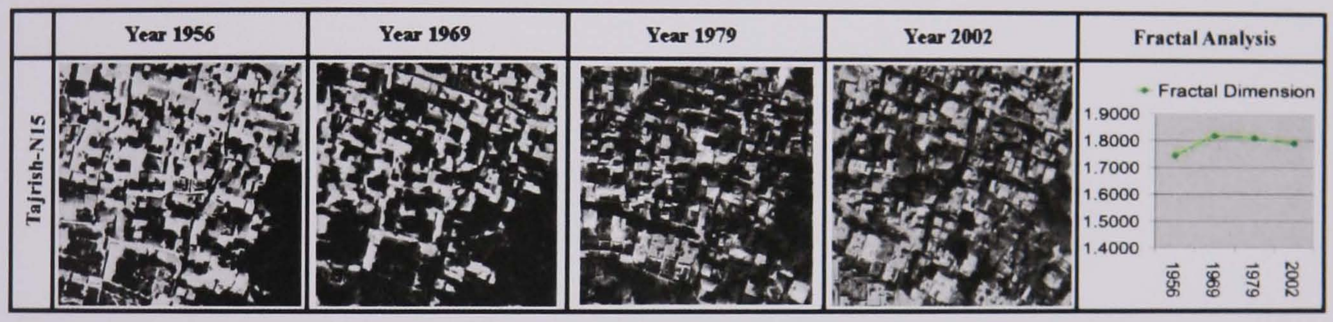
1.5000
1.4000
1956
1969
1979
2002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Year 1969
Year 1979
Year 2002
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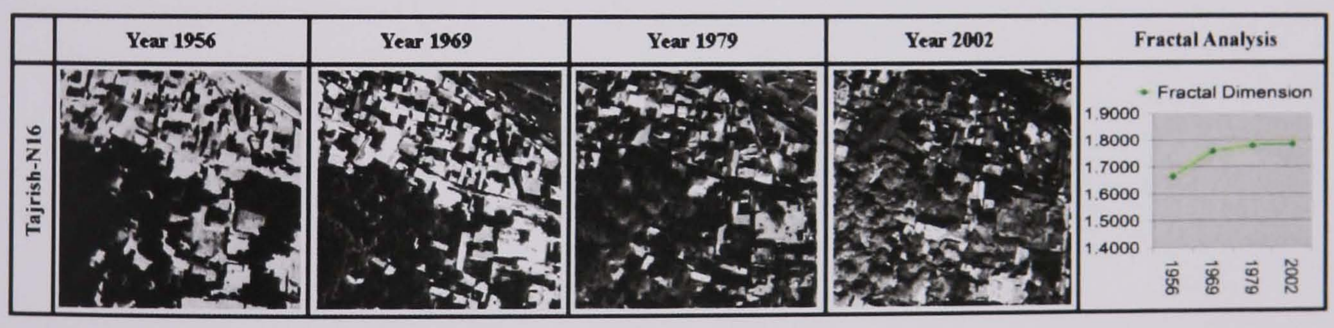
1.4000
1956
1969
1979
2002


Tajrish-N16
Year 1956
Year 1969
Year 1979
Year 2002
Fractal Analysis
Fractal Dimension
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1.8000
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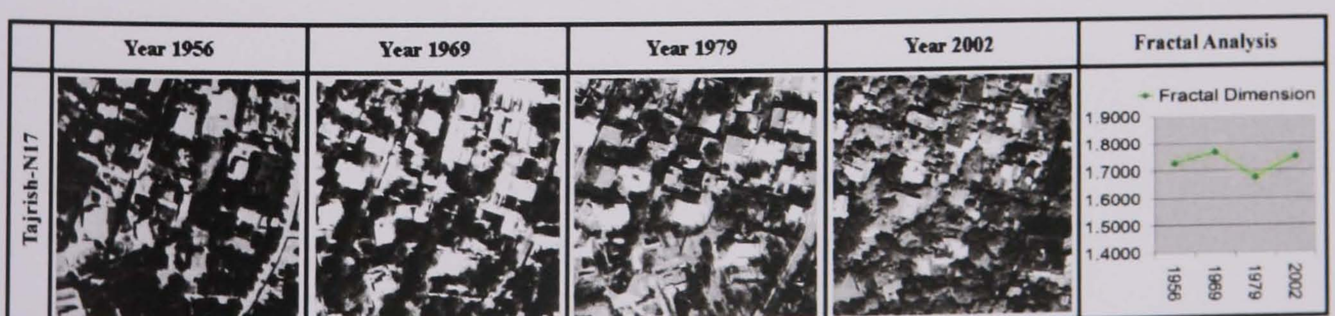
1.6000
1.5000
1.4000
1956
1969
1979
2002


Tajrish-N17
Year 1956
Year 1969
Year 1979
Year 2002
Fractal Analysis
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1.6000
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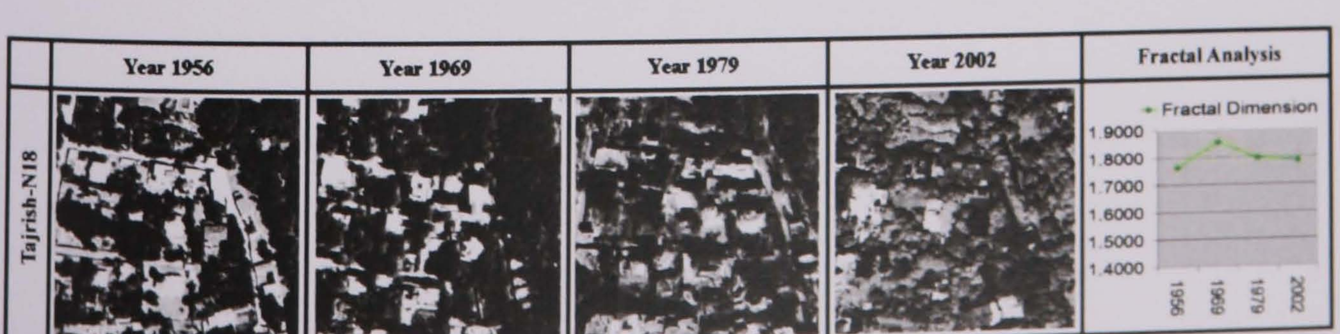
1.4000
1956
1969
1979
2002


Tajrish-N18
Year 1956
Year 1969
Year 1979
Year 2002
Fractal Analysis
Fractal Dimension
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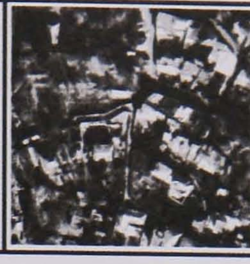
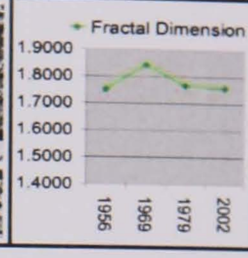
1.8000
1.7000
1.6000
1.5000
1.4000
1956
1969
1979
2002

	Year 1956	Year 1969	Year 1979	Year 2002	Fractal Analysis
Tajrish-N19					

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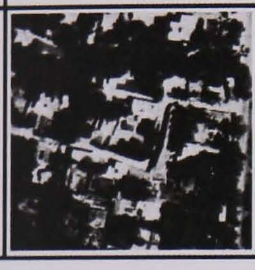
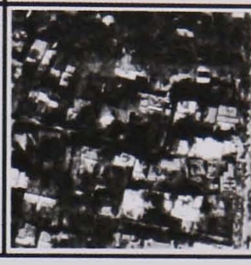
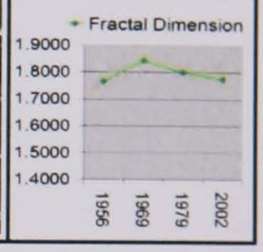
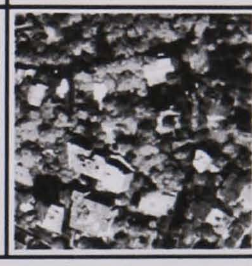
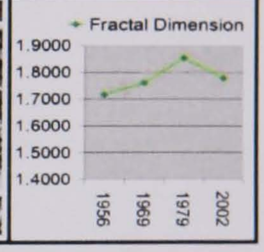
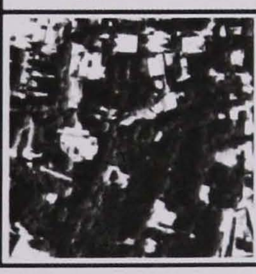
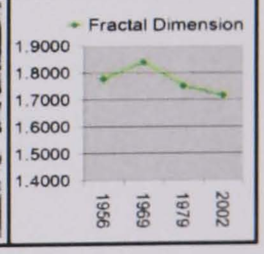
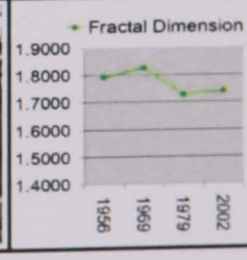
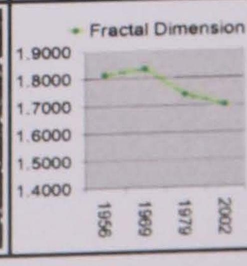
Tajrish-N20					

	Year 1956	Year 1969	Year 1979	Year 2002	Fractal Analysis
Tajrish-N21					

	Year 1956	Year 1969	Year 1979	Year 2002	Fractal Analysis
Tajrish-N22					

	Year 1956	Year 1969	Year 1979	Year 2002	Fractal Analysis
Tajrish-N23					

	Year 1956	Year 1969	Year 1979	Year 2002	Fractal Analysis
Tajrish-N24					

APPENDIX G

THE PUBLISHED PAPER IN 2006: CONTROLLING FUTURE URBAN DEVELOPMENTS BY FRACTAL DIMENRIONS

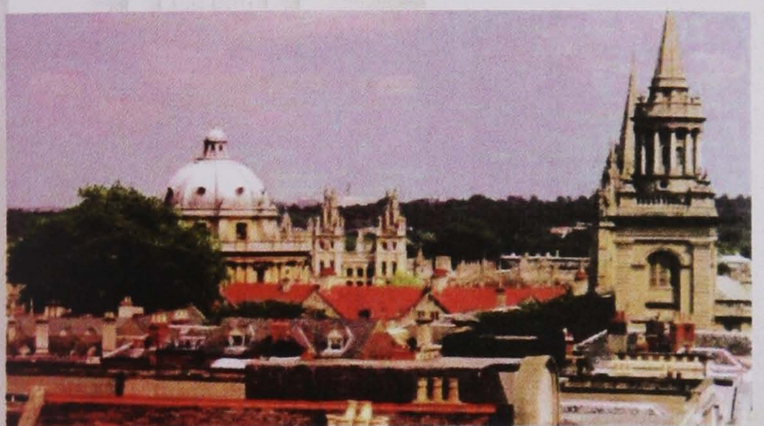
شهرسازی و GIS

سال پنجم: اسفند ۱۳۸۴

۵۰۰ تومان

شهرنگار ۳۴

نشریه علمی پژوهشی مرکز اطلاعات جغرافیایی شهر تهران



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کارکرد خدمات شهری در مدیریت بحران

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In His Name,the Exalted

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تنظیم : شیلا فرخ نیایی
کارشناس برنامه ریزی شهری واحد مدیریت شهری

طوفان حقانی:
با محاسبه بعد فراکتالی می توانیم تغییرات آتی شهرها را کنترل کنیم

مهندس طوفان حقانی، در دوره دکترای دانشگاهUCE بیرمنگام با موضوع رساله« کاربرد تئوری آشوب و هندسه فراکتال در شهرسازی (طراحی شهری)» به تحصیل اشتغال دارد.ایشان مدرس دانشگاه هنر نیزمی باشد. در این رساله ، ابعاد فراکتالی شهرمورد ، مطالعه قرار گرفته و مورفولوژی شهری (ریخت شناسی) از دیدگاه تئوری آشوب (نظم در آشفتگی) و هندسه نوین فراکتال ها بررسی می شود. این موضوع در تاریخ۸۴/۹/۱۲ در سالن آمفی تئاترشرکت پردازش و برنامه ریزی شهری در ۵ محور ارائه شد:

۱. تاریخ تئوری آشوب و هندسه فراکتال
۲. مصداق تئوری آشوب و هندسه فراکتال در معماری و شهرسازی
۳. کاربرد تئوری آشوب و هندسه فراکتال در نمونه موردی (شهر تهران)
۴. جمع بندی
۵. پرسش و پاسخ

پرسش و پاسخ هایی که پس از ارائه سخنرانی مطرح گردید در متن ذیل گنجانده شده است.

تاریخچه

آشوب (Chaos)

جیمز گلیک(۱)، اعتقاد دارد که اگر قرن بیستم را به دلیل ارائه نظریه کوآنتوم و تئوری نسبیت، قرن

تحول بزرگ در فیزیک بدانیم، قرن بیست و یکم قرن تئوری آشوب خواهد بود. پیدایش تئوری آشوب به دیدگاه جدیدی که انسان در فیزیک به دست آورده است، برمی گردد. منظور از دیدگاه جدید، تغییری است که در دیدگاه نیوتنی و لاپلاسی از اوایل قرن بیستم ایجاد شد. بر اساس دیدگاه نیوتنی، اگر ما تمام نیروهای وارد به یک جسم را بشناسیم، می توانیم حرکت آن جسم را پیش بینی کنیم. لاپلاس اشاره می کند که" اگر ابرمردی بتواند تمام نیروهای حاکم بر طبیعت را شناسایی کند، می تواند به وسیله آن آینده را پیش بینی کند."

ولی در قانون دوم ترمودینامیک، دانشمندان به این نکته پی بردند که برخی از سیستمها صد در صد قابل پیش بینی نیستند و آن به دلیل انرژی است که سیستم از دست میدهد. ضریب خطای درون سیستم را آنتروپی (Entropy) نامیدند. و این مسئله در اواسط قرن بیستم جرقه ای بود برای شناسایی سیستمهای آشوبناک Chaos)) یا نظم در آشفتگی(۲) .

به عنوان مثال کارخانه ای را در نظر بگیرید. اگر در این کارخانه، یک اخلال (Noise) ایجاد شود، ممکن است کل سیستم از کار بیفتد. حال آنکه اگر در یک سیستم زنده (مانند باکتری ها، گیاهان، بدن انسان، حرکت سیارات و ...) اخلالی ایجاد شود سیستم از کار نمی افتد، بلکه این محیط ها، به اخلال پیش آمده پاسخ داده، نظم جدیدی ایجاد می نمایند. اگرچه این Noise می تواند سیستم را از مسیر اولیه منحرف کند. یکی از مهمترین مثال ها در این تئوری اثر پروانه ای (Butterfly effect) است. این مثال، چنین عنوان می کند که اگر یک پروانه در توکیو از شاخه ای به شاخه دیگر پرواز کند، اثر آن بصورت ایجاد انحراف در سیستم، میتواند در سرزمین دیگری ایجاد طوفان نماید. زمانی که تعداد اخلال های ایجاد شده زیاد باشد، بر تعداد آنتروپی ها اضافه می شود و در نتیجه پیش بینی با مشکل روبرو می شود، دلیل مهمتر برای این پدیده این است که اصولا" سیستم های آشوبناک، بسیار وابسته و حساس به شرایط اولیه خود هستند (۳).

اخلال ها بصورت تصاعدی در طول تناوب سازمان افزایش می یابد. به همین دلیل است که در این سیستم ها (به عنوان مثال در هواشناسی) برای بلند مدت پیش بینی امکان پذیر نمی باشد. لورنز در این زمینه می گوید: عملا"خیلی از انتظاراتی که از فرمول ها می رود، در محیط واقعی دقیق عمل نمی کند. اساس سیستم های فعال در طبیعت پیرامون ما، بازی بین نظم و بی نظمی است. سیستم های زنده به همان اندازه که به نظم درون ساختار خود وابسته اند از بی نظمی های موجود در محیط نیز بهره می برند. به عنوان مثال در سیستم قلب، پزشکان بارها توانسته اند افراد سکته کرده را با یک شوک الکتریکی به حالت طبیعی برگردانند.

فراکتال (Fractal)

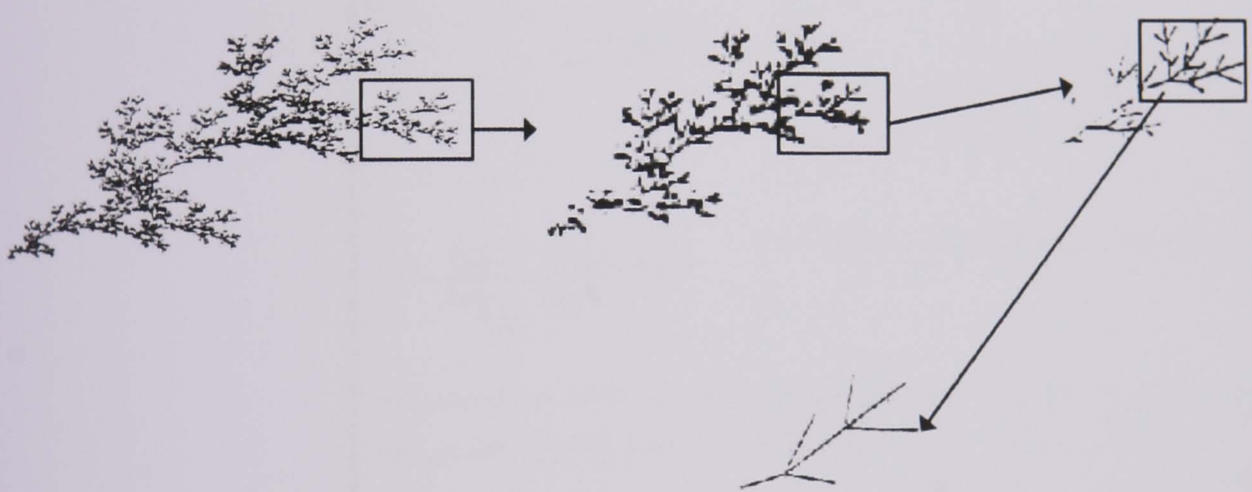
هندسه فراکتالی (۴)، در واقع هندسه حاصل ازیک فرایند آشوبناک است.

"آیا هیچ توجه کرده اید که چرا ما اکثرا هندسه اقلیدسی را هندسه ای سرد و خشک می دانیم؟ "

در سال ۱۹۷۰ ریاضیدانی به نام مندل بروت (۵)، در مقدمه کتاب معروف خود "هندسه فراکتالی طبیعت" در پاسخ به سؤال فوق می گوید هندسه اقلیدسی نمیتواند اشکال طبیعی را بررسی کند. هیچ کوهی مثلث، هیچ ابری بیضی یا هیچ گردویی کروی نیست. در عین حال در طبیعت هارمونی، هماهنگی و جذابیت شگفتی بین اجزاء مناظر طبیعی وجود دارد که برخلاف هندسه اقلیدسی در چشم آدمی جذاب است. به عنوان مثال ترک های کوه، غیر منظم و تصادفی نیست. شاخه شاخه شدن ساقه درختان نیز از

هندسه ای منظم اما غیر اقلیدسی تبعیت می کنند. این هندسه علی رغم ظاهر بی نظمش از تعادل بین نظم وتصادف به وجود می آید. هندسه فراکتالی در میکرو ساختارها مانند باکتری ها ، نحوه انشعاب در شش انسان، شاخه شاخه شدن یک درخت و در ماکرو ساختارها، شکل گیری کوه ها و حتی در مقیاس بزرگتر کهکشان ها، قابل مشاهده است.

خود شبیه بودن (Self Similarity) مشخصه اصلی اشکال فراکتالی است. در یک شکل فراکتالی، خصوصیت خود شبیه بودن بین اجزاء و کل شی وجود دارد. مثلا شکلی که از یک شاخه درخت سرو به دست می آید با کل شکل شاخه شباهت دارد. این وضعیت در شاخه های کوچکتر هم دنبال می شود (شکل ۱).



شکل ۱) ویژگی خود شبیه بودن در درخت سرو

پس می توان نتیجه گرفت که فرم های طبیعی الگوی تکرار شونده دارند. خود شبیه بودن با مثل هم بودن تفاوت دارد. هیچ دو شاخه درخت سرو مثل هم نیست ولی شبیه هم هستند، به عبارتی فراکتال در مورد روابط و هندسه اشکال صحبت می کند.

بعد فراکتالی (Fractal Dimension)

برای بررسی تئوری آشوب در معماری و شهرسازی، کلمه کلیدی بعد فراکتالی مطرح می شود. در جهانی که زندگی می کنیم، بعد صفر (برای نقطه)، بعد۱ (برای خط)، بعد۲ (برای نقطه)،بعد ۳ (برای حجم سه بعدی) را می شناسیم.

دانشمندان ثابت کرده اند که جهان ما، کاملا" سه بعدی نیست و ابعاد بینابینی را نیز دارا می باشد. به عنوان مثال، یک درخت، سه بعد را کامل پر نمی کند و ابعادش خرد شده است.

بعد فراکتالی از رابطه $D=\frac{\log N}{\log \frac{1}{s}}$ به دست می آید که در آن، تعداد اشکال = N و تعداد قطعات = S است.

یکی از مثالهای کلاسیک در تعیین بعد فراکتالی، مثال Koch Curve می باشد (شکل ۲) .

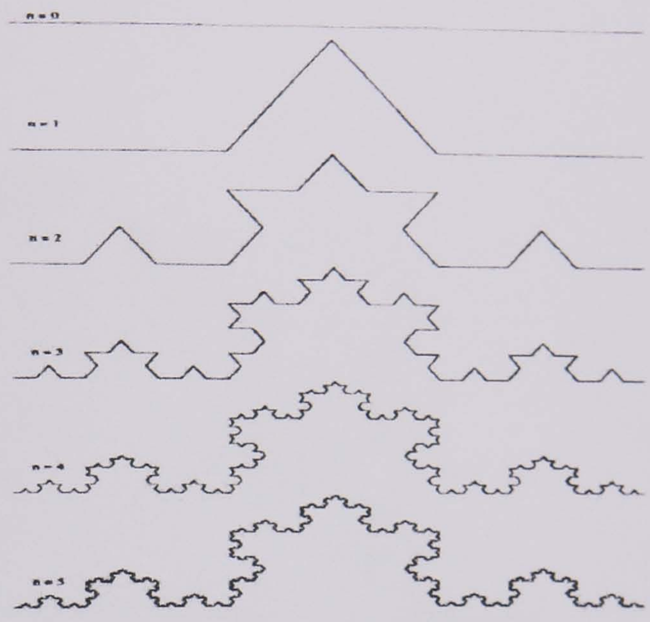


FIGURE 2.8: Construction of the triadic Koch curve.

Koch Curve (شکل ۲)

بعد واقعی شکل بوسیله رابطه لگاریتمیک زیر قابل محاسبه است:

$$D=\frac{\log ۴}{\log \frac{۱}{۱/۳}}=\frac{\log ۴}{\log ۳}=۱/۲۶$$

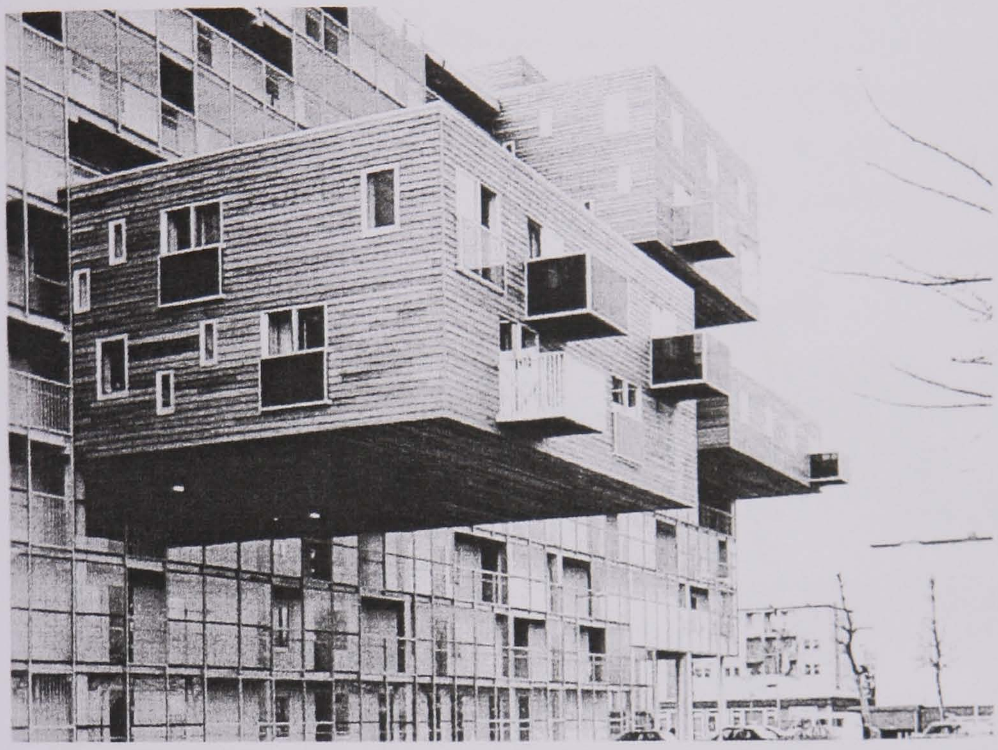
نکته جالب در این اشکال آن است که امکان تکراراشکال تا بینهایت وجود دارد. با دقت در طبیعت و اجزا آن، اشکال خود شبیه در جزئیات و در مقیاسها یا لایه های مختلف یک ساختار فراکتالی یافت می شود که این خصوصیت را عمق پذیری می گویند.

کاربرد تئوری آشوب در معماری و شهرسازی

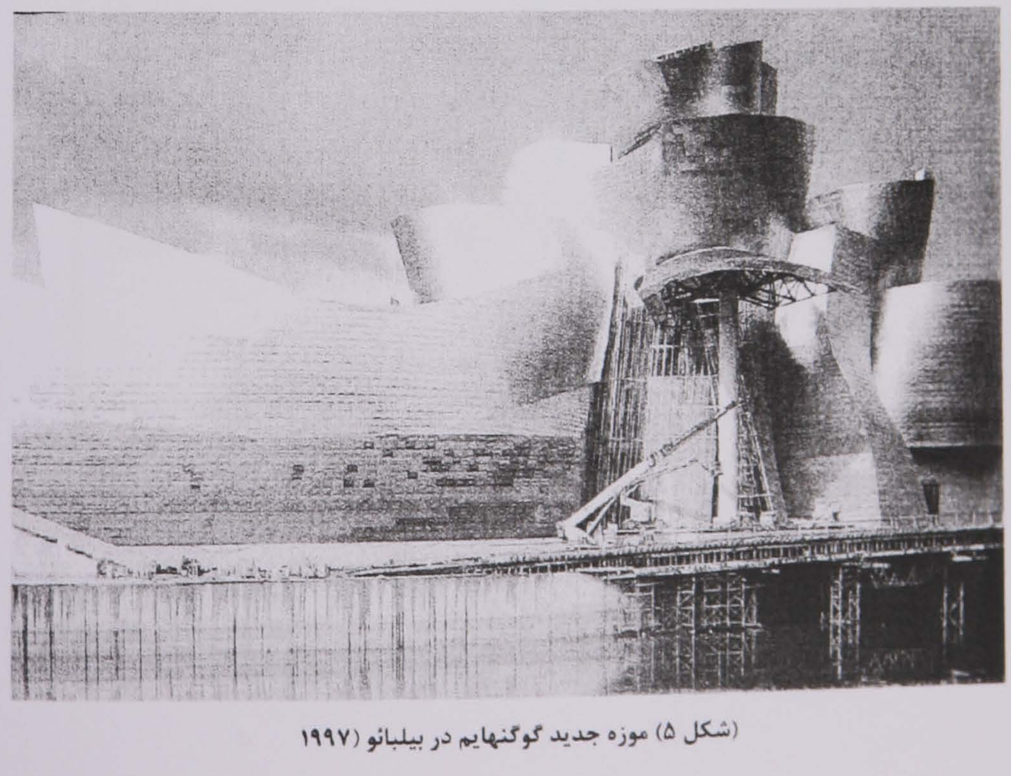
کاربرد در معماری

بسیاری از معماران از ویژگی خود شبیه بودن استفاده کرده اند، همانند ساختمان یادبود در پاریس (شکل ۳)، مقرنس کاری های اسلامی، پنجره های ساختمان های دوره صفوی، ساختمان مسکونی در آمستردام (شکل۴)، موزه گوگنهام دربیلبائو (شکل۵) و ...

شکل ۳) عمارت یادبود Thiepvalسال ۱۹۲۵

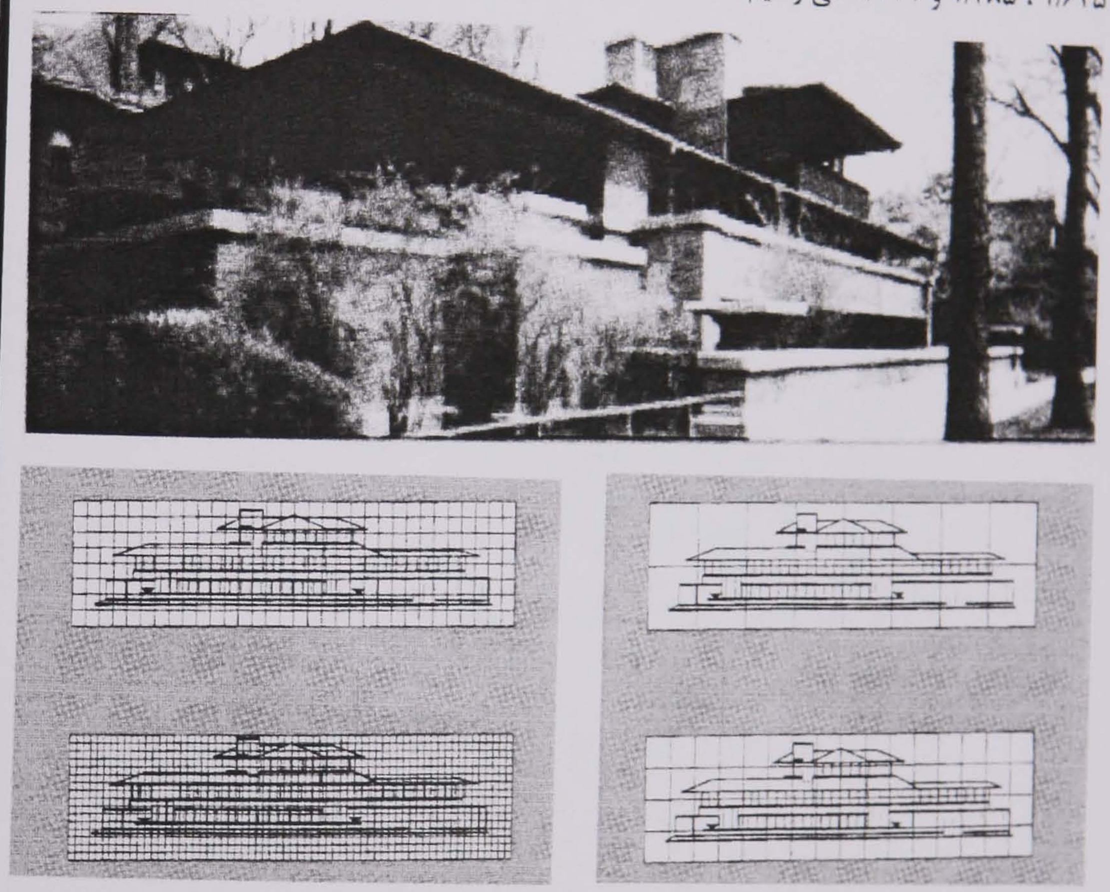


شکل ۴) ساختمان مسکونی در آمستردام (MVRDV ۱۹۹۵)



(شکل ۵) موزه جدید گوگنهایم در بیلبائو (۱۹۹۷

در موزه جدید گوگنهام، با استفاده از منحنی های تکرار شونده، یک نوع هندسه کهکشانی ایجاد گردیده و فرم هایی شکل گرفته که شبیه به هم ولی در اندازه های مختلف بکار برده شده اند. در تمامی این نمونه ها، آگاهانه یا نا آگاهانه معماران سعی کرده اند در طراحی ازاین خاصیت عمق پذیری که همان زبان سازنده طبیعت است، استفاده نمایند. این امر بابررسی میزان پیچیدگی فرم ها ومحاسبه خاصیت عمق پذیری نیز قابل اثبات است.کارل بوویل در کتاب Fractal Geometry in Architecture and design، بعد فراکتالی آثار معماران معروف را محاسبه و با هم مقایسه کرده است. به عنوان مثال اگر دو مقیاس مختلف خانه Robie اثر لوید رایت مبنای محاسبه قرار گیرد(شکل ۶)، به ابعاد فراکتالی ۱/۶۴۵ ، ۱/۴۸۵ و ۱/۴۴۱ می رسیم.



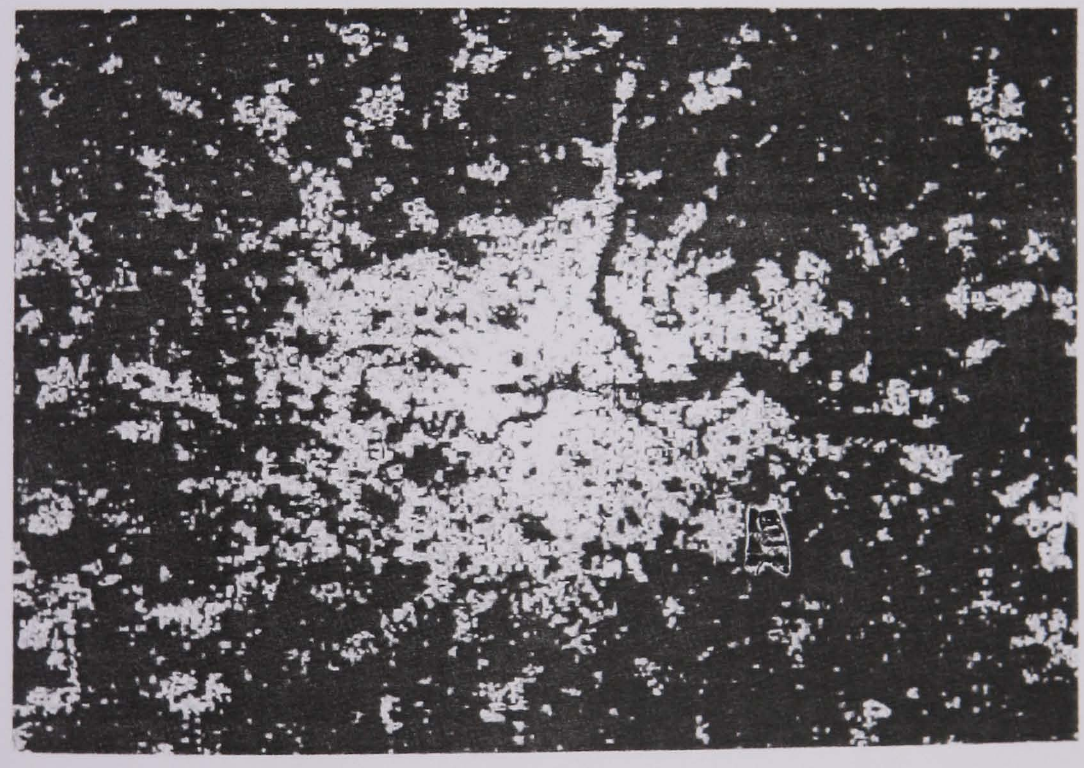
(شکل ۶)خانه روبی اثر فرانک لوید رایت

در دیگر آثار معماران مدرن پیشگام، به دلیل تاکید بر ساده گرایی (Purism) کمتر خاصیت عمق پذیری دیده می شود. مثلا در مورد ویلا Savoya اثر لوکوربوزیه به ابعاد فراکتالی ۱/۴۲۲، ۱/۲۳۳، ۱/۰۰۰ می رسیم و این شاید به این دلیل است که ویژگی عمق پذیری درجزئیات در کارهای رایت بیشتر از لوکوربوزیه دیده می شود. بنابر این بی دلیل نیست که تئوریسین ها، آثار فرانک لوید رایت را همساز با طبیعت می دانند. بحث فراکتال در معماری بیشتر دارای جنبه زیبا شناسی است و معماران سعی می کنند با الهام از طبیعت، فرمی را ایجاد نمایند که بازگو کننده زبان معماری طبیعت باشد.

کاربرد در شهرسازی

در شهرسازی، این تئوری ها تنها جنبه زیبایی شناسی مطرح ندارند و جنبه عملکردی هم به آن اضافه می گردد. بنابراین اهمیت تئوری آشوب در شهرسازی ، در پاسخ به پرسش های زیر، با ارزش تر و مهم تر کاربرد این تئوری در معماری است. آیا می توانیم شهرها را هم مثل سیستم های زنده در نظر بگیریم؟ آیا ممکن است در جزء و کل الگوی شهری، روابط خود شبیه بودن را پیدا نمود؟ و بالاخره آیا تئوری های فوق میتوانند تغییرات در شکل شهرها را با ابزاری دقیق تر اندازه گیری و محاسبه کنند؟

یکی از کاربردهای تئوری آشوب در شهرسازی، توسعه سلول شهری است. بدین معنا که شکل شهر براساس تکرار یک سلول زاینده در محیط کامپیوتری براساس قواعدی که از پیش تعریف شده، شبیه سازی می گردد دکتر مایکل بتی (۶) در مقاله ای تحت عنوان "From cells to cities" به شبیه سازی شهر به شکل سلول های زاینده ای که تکثیر می شوند می پردازد. پروفسور بتی و همکارانش در دانشگاه لندن این امر را با روش CA(Cellular Automata) انجام داده اند. در شکل ۷ ،تصویر شهر لندن، با این روش ساخته شده است که در آن مدلهای خوشه ای (Cluster Models) براساس رفتار فراکتالی در جهات مختلف رشد داده شده است



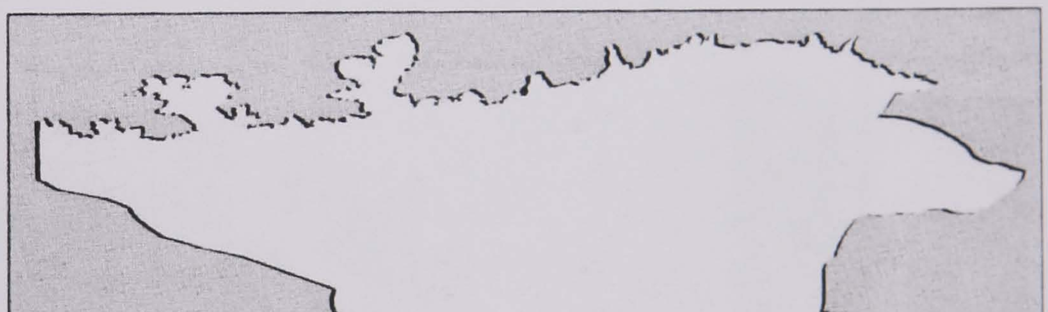
(شکل ۷) مدل فرکتالی شهر لندن

در دانشگاه UCE بیرمنگام نیز نرم افزاری تحت عنوان CAST (City Analysis Simulation Tools) در حال تهیه و تولید است که با استفاده از آن بتوانند، رفتار شهر را در برخورد با هر تغییر احتمالی دقیق تر بررسی کنند. از آنجا که بر مبنای تئوری آشوب در بلند مدت نمی توان آینده سیستم های زنده را پیش بینی کرد بنابراین تنها برای یک دوره کوتاه مدت (مثلا ۱۰ یا ۱۵ ساله) رفتار شهر را می توان پیش بینی نمود. بررسی مزایای فراکتال در شهرسازی و طراحی شهری، یک کار جدیدی است که جای توسعه دارد.

برخی از مزایای فراکتال در شهرسازی، در رساله دکتر جاناتان کوپر(۷) از دانشگاه آکسفورد بوروکس عنوان شده است. به عنوان مثال یکی از کاربردها این است که اگر در طرحی، خیابانی از وسط یک بافت عبور کند، کاربری های اطرافش هم، عمومی تر می شود و نوع و اندازه سلول ها تغییر می کند. به نرم افزار برنامه می دهند و پیش بینی می کنند که اگر خیابان ساخته شود، شکل شهر در ۲۰-۱۰ سال آینده چه تغییری می کند. همیشه این سؤال مطرح است که آیا روش فراکتال فقط برای شهرهای ارگانیک قابل استفاده است یا برای شهرهای از پیش برنامه ریزی شده هم کاربرد دارد؟ عملا ثابت شده است که شهرهای از پیش برنامه ریزی شده به مرور زمان به صورت فراکتال گسترش می یابند، هرچند در بدو امر که ابداع می شوند غیر فراکتال هستند.

کاربرد تئوری آشوب و هندسه فراکتال در نمونه موردی (شهر تهران)

کاری که در این رساله در حال انجام است، شناخت تغییرات شکل شهر تهران با نگاه فراکتالی است. رشد، تغییرات و پراکنش فعالیت ها و عناصر شهری را در تهران با استفاده از این تئوری ها می توان اندازه گیری کرد. از جمله فواید این روش، شناسایی پیچیدگی های مرز یا خط محدود کننده شهر (urban boundaries)است. محاسبه فراکتالی روی محدوده قانونی شهر تهران نشان می دهد هرچه به مرز های طبیعی شهر نزدیکتر می شویم، خصوصیات فراکتالی بیشتر می شود و در جاهائی که توسعه شهری به صورت خطی انجام می شود، بعد فراکتالی کمتر است(شکل۸). این خود گویای اینست که رشد ارگانیک و تدریجی بافت محلات شهری در همجواری عوارض طبیعی وجغرافیایی، پیچیدگی یا خاصیت عمق پذیری بالاتر و در جاهائی که توسعه شهری به صورت سریع و خطی است،شاخص فراکتالی پایین تر است.



شکل ۸)بعد فراکتالی خطوط محدوده شهر تهران

براساس تحلیلی که بر روی اندازه قطعات تفکیکی و پراکنش آن صورت گرفته(۸)این نتیجه حاصل گردیدکه درقطعات ۱۰۰ تا۳۰۰ و۳۰۰ تا۱۰۰۰ مترمربعی که مربوط به رشد تدریجی بافت ارگانیک شهری است، شاخص فراکتالی بزرگتر و قطعاتی که بزرگتر از ۵۰۰۰ مترمربع و مربوط به مناطق تازه توسعه یافته است و همچنین از هندسه اقلیدسی تبعیت می کنند، شاخص کوچکتر است (جدول ۱).

Plot Grain	Year	Fractal dimension
Pa<100	1940-1978	1.599
100<Pl<300	1951-1920	1.608
300<Pl<1000	1960-1996	1.592
1000<Pl<5000	1921-1950	1.562
Pl>5000	1970-1996	1.368

جدول شماره ۱) ارتباط بین متراژ زمین و بعد فراکتالی

پس به طور کلی در مناطق ارگانیک، بعد فراکتالی بیشتر و در مناطقی با هندسه از پیش برنامه ریزی شده (به طور مثال منطقه ۲۲) بعد فراکتالی کمتر است. در بخش دیگری از این مطالعات، منطقه تجریش به دلیل وجود هر دو حالت ارگانیک و از پیش برنامه ریزی شده، انتخاب گردید. اگر به نقشه حومه تجریش نگاه کنیم (شکل ۹)، یک سری الگوهایی در حال تکرار مشاهده می شود. این فرم ها شبیه به مربع است که در جهات مختلف در حال تکرار است که اصطلاحا" به این الگو (Patterns Generator) می گویند.

شکل ۹)الگوهای فراکتالی تکرار شونده در بافت تجریش

به عبارتی ویژگی خود شبیه بودن در مقیاس های مختلف در منطقه تجریش کاملا" قابل مشاهده است. مقدار فراکتالیته بافت تجریش با کمک نرم افزاری بنام Benoit، بدست می آید. نرم افزار، براساس رابطه لگاریتمی بین مقیاسهای متفاوت، بعد فراکتالی را تعیین می نماید.

محاسبه بدین صورت است که هر ۵-۴ خانه را یک واحد همسایگی درنظر می گیریم. نقشه تهران به صورت یک فایل BMP به نرم افزار Benoit داده می شود و این نرم افزار، به اندازه گیری میزان عمق نقشه می پردازد. البته این نرم افزار Object Baseنیست بلکه به صورت پیکسل به پیکسل عمل می کند و فضاهای پر و خالی را به صورت صفر و یک شماره گذاری می کند. در نهایت تعداد خانه های پر به تعداد خانه های خالی در مقیاس های مختلف در یک تناسب لگاریتمی اندازه گیری میشود و بدین ترتیب بعد فراکتالی به دست می آید. اگر ما ۲ مقیاس متوالی داشته باشیم می توانیم عدد فراکتالی را محاسبه کنیم، حال آنکه Benoit برای دقت بیشتر این عمل را ۲۵ تا ۳۰ بار در مقیاسهای متفاوت تکرار می کند. اگر به ترتیب در مقیاس های همسایگی، محلی، منطقه ای و شهری بعد فراکتالی را محاسبه کنیم، یک کد شهری به دست می آید که منحصر به یک واحد همسایگی مشخص است و آن را می توان به مثابه DNA کالبدی در نظر گرفت. به عنوان مثال بعد فراکتالی به دست آمده برای اطراف امامزاده صالح ۸۰۶-۶۳۰-۵۶۲-۶۹۱ می باشد و آن را اصطلاحا FNID (۹) یا شناسه فراکتالی در واحد همسایگی می نامیم. در حقیقت می توان بدین وسیله محدوده یک محله را براساس ویژگی های کالبدی آن و نه براساس خط و محدوده قانونی شناسایی کرد. روشی که در این رساله پیشنهاد می شود را می توان برای پرسپکتیوها و نماهای شهری، شبکه های ارتباطی، خیابان و دسترسی های محله ای، لبه ساختمان‌ها، فضای سبز شهری، خط آسمان به کار برد و برای یک محله خاص شناسه های فراکتالی تهیه کرد. اگر منظور حفظ هویت کالبدی محلات باشد، محاسبه بعد فراکتالی، به ما امکان می دهد که بتوانیم تغییرات آتی را کنترل کنیم. به عنوان مثال اگر بخواهیم ساختمان جدیدی در تجریش ایجاد کنیم، به جای استفاده از قوانین تراکم ساختمانی ۶۰٪ فعلی، میتوان از شناسه فراکتالی به عنوان ابزاری مکمل در کنار دیگر قوانین و ضوابط حاکم استفاده نمود. بدین معنا که طرح هایی که باعث تغییر شدید شاخص FNID می شوند، رد شوند. این مطالعه نه تنها قابل تعمیم به کل شهر تهران است بلکه این روش قابل استفاده برای شهرهای دیگر نیز می باشد. هرچه نقشه ها به روزتر و دقیق تر باشد و پیکسل ها با دقت کامل تری برداشت شده باشند، عدد فراکتالی به دست آمده، معتبرتر است.در اینجاست که نقش GIS و نیاز به روز بودن آن مطرح می شود. در ضمن باید در نظر داشت بحث فراکتال، بحث آخر و تمام کننده نیست.یک المان و یک وسیله مکمل در دست معمار و شهرساز است که از آن می‌تواند در پروسه ای که طراحی می‌کند به عنوان یک قید استفاده نماید.

جمع بندی

۱. شهرها به مثابه یک موجود زنده و پویا به صورت فراکتالی رشد و تغییر می کنند.

۲. آنالیز، پیش بینی و شناخت یک شهر بوسیله هندسه فراکتالی نسبت به هندسه اقلیدسی واقع بینانه تر و دقیقتر است.

۳. استفاده از تئوری آشوب و فراکتال ها با نگاهی دو سویه (جزء به کل و بالعکس) و با کنترل تغییرات در مقیاس همسایگی ابزاری بهتر برای بررسی رشد و کنترل تغییرات آتی کلانشهرها است.

۴. FNID یا شناسه فراکتالی، شاخص مناسب تری برای شناخت ویژگی های کالبدی فضاهای شهری است.

پاورقی و یادداشت ها

۱ James Gleick

۲ نظم در آشفتگی ترجمه ای است که آقایان دکتر قدمی و نیازمند برای کتاب "Chaos" نوشته جیمز گلیک انتخاب نموده اند

۳ Sensitivity to the Initial Conditions

۴ مندل بروت برای اولین بارلغت فراکتال را از ریشه لاتینی Fractus به معنی خرد شده‌ابداع کرد

۵ Benoit Mandelbrot

۶ Michael Batty

۷ Jonathan Cooper

۸ با استفاده از نقشه های تهیه شده در مهندسین مشاور شاران

۹ Fractal Neighborhood Identification code

منابع

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APPENDIX H

THE PUBLISHED PAPER IN 2004:
THE NATURE OF
URBAN MORPHOLOGICAL EVOLUTION
BASED ON
CHAOS THEORY AND FRACTAL GEOMETRY

THE NATURE OF URBAN MORPHOLOGICAL EVOLUTION BASED ON CHAOS THEORY AND FRACTAL GEOMETRY

Fractal dimension assessment of urban environment at the street Level for the case study of Tehran, Iran

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Abstract. Chaos and fractal theory allow the conceptualization, evaluation and simulation of complex, irregular, live systems such as cities. This paper intends to highlight some current researches, which examined fractal applications and their links with urban design and analysis. It proposes a new method for physical surveys of the building forms and the street patterns in the north of Tehran, Iran, based on fractal Geometry. It employs a fractal calculator (Fractal software) to facilitate the fractal dimension measurements of Tehran urban environment in order to identify a specific fractal fingerprint, in terms of *'Fractal Neighborhood Identification code'* (FNID) at the street level. Then it applies the method to selected streets within the case study for measuring the degree of homogeneity or heterogeneity that they display according to their range of building types. Finally it constructs a platform base for examining more accurately urban forms, and evaluating quantitatively urban change and development.

1. Introduction

Towns and cities are complex systems. They are the product of different factors such as politics, economics, technology, fashion, culture, climate, etc. However, until relatively recently they have not generally been treated as complex systems. The planners, designers and builders of settlements treated them as simple predictable systems to be ordered and reduced to its components to facilitate modeling and manipulation.

Batty (1994) wrote 'For generations, architects and planners have attempted to impose a simple, smooth, visual order on cities in the belief that such order counters the disorder and dysfunction which cities reveal when they develop 'naturally'. Klinger and Salingaros (1999) wrote the greatest creation of humanity –their buildings, cities, artworks, or artifacts- are neither simple nor random, but have a high degree of organized complexity. Chaos and fractal theory help us to conceptualize, evaluate and simulate complex, irregular systems like those exist within cities.

The main proposition of this paper is that cities' growth implies a systematic order at each level of their hierarchy. In other words, contained within the growth process are codes, which determine how the organization of these basic units of urban development might repeat their form and function in many scales where subsequently result a unique geometric pattern for each part of a city. The method proposes here, is an attempt to evaluate quantitatively city patterns by measuring mathematically their fractal dimensions and by transferring their geometric forms to the numerical codes extracted from existing fractal pattern of them. The term 'FNID', *Fractal Neighborhood Identification code*, will be defined in this paper, as a kind of fingerprint for each part of city, by which mathematically one could measure the degree of complexity that each part demonstrates at local neighborhood level of Tehran's streets. In Section 2.1 and 2.2 a brief definition for fractal geometry and chaotic systems will explain how these new theories has shifted our conventional views towards more realistic understanding of city form and function.

Furthermore it explains the ability of this method to explore other city's physical features such as plans, elevations, skylines... and the possible link between their visual appearance and their fractal dimension by which it might be typified. Fractal dimension assessments of environment, also assists urban designers to test their design products and evaluating the level of harmony achieved by a set of building combination of different type within an urban realm.

2. Theoretical Background:

A number of authors such as Lynch (1961, 1981), Alexander (1987, 2000) have attempted to recognize the real world complexity of the cities. Lynch (1961) investigated the psychological complexity of the city in terms of how people navigate their way around a place. Alexander (1987) sought to discover, through the development of a "pattern language" combining urban elements, the quality without a name that makes a place special. Bovill (1996) have developed a design method that attempts to deal with the complexity of a place in terms of its function, appearance and structure. Each of these approaches has the common characteristics of trying to deal with urban places as combination of elements e.g. buildings, spaces, natural features, meaning and symbols.

More recently Authors Batty (1991, 1994, 1996, 1999), Bovill (1996), Jencks (1997) and Salingaros (1999, 2003) and Cooper (2000, 2003) recognizing the complex nature of the city, have suggested the emerging new sciences of Chaos and Fractals, as means of dealing with complexity in planning and design. Many of these attempts are now concentrating on city simulations (e.g. recent work in UCL, London) and developing Cellular Automata tools; It is based on the concept that, city evolution at large scale is traceable by following the sequence of changes occur in small scale units (cells) within it (Batty & Xie, 1994). Therefore since the last two decades, there have been a number of attempts, connecting micro scales to the macros, however, some followed by the notion of finding a kind of DNA signature for cities (Webster, 1995). These together with Cooper's work on fractal analysis of Oxford streets directed my research towards exploring fractal dimensions within the urban realm, and specifying a kind of fingerprint for each urban apace in terms of 'FNID'. It provides an appropriate tool for controlling the large scale changes in urban growth by controlling the changes occur in small scale units at local neighborhood level.

2.1. CHAOS THEORY

Both chaos and fractals describe complex systems, chaos describing the processes of changes affecting a system while fractals illustrating the resultant patterns. Chaos might be defined as the unpredictable behavior of nonlinear, complex and dynamical systems. Grace (1991) wrote "*chaos*" *is* about the study of nonlinear dynamic systems and deals with irregular and unpredictable behavior rather than trying to reduce complex systems to linear cause and effect relationships. In addition to "Unpredictability", Glick (1987) listed "Emergence", "Self organization", 'Adaptability' and "Irreducibility", as some of other characteristics of nonlinear chaotic systems. All these can arguably be observed in the city. In another words, urban systems manifest the characteristics of nonlinear chaotic systems, they are argued to have a self organizing nature; they can emerge, organize and evolve, without a preconceived master plan, yet across both time and space.

One the main characteristic of such a system is irreducibility. A non-linear system can not be reduced to its component parts; in this sense the whole is more than the sum of its part. Jan Walleczek (2000) argued the concept that the dynamical interactions between dependence elements at a local microscopic level influence and influenced by the emergent global structure at the macroscopic level. Through the continuing interactions interplay between micro and macro processes the emergent; self-organizing structure is stabilized and actively maintained. In a city it means that it is impossible to take the plans of a single house and from them deduce the totality of the city. The position of that house and its subsequent neighbors will be subject to a range of many agents in making decisions about the location. However, the way we controls the changes occur in small scale units at local neighborhood level, is an effective way to control the large scale urban changes. As Batty and Longley (1994) believe cities in general, evolving and changing according to their local rules and conditions which manifest more global order across many scales and times.

2.2. FRACTAL GEOMETRY

A mathematician, Benoit Mandelbrot, first suggested the term "fractal" in 1977, he mentioned that 'a fractal is a shape made of parts similar to the whole in some way' (Feder, 1988, p11). In another words there is self-similarity over deferent scales of a fractal object. Mandelbrot (1982) argued that many of *irregular* and *fragmented* patterns around us in the nature could be described by fractal geometry. It helps us to study those form that Euclid leaves aside as being formless or morphologically amorphous.

According to Barnsley (1993) classical geometry (Euclidian geometry) provides a first approximation to the structure of physical objects; this is the language we use to communicate the designs of technological products and, very approximately, the forms of natural creations. Fractal geometry is an extension of classical geometry. It can be used to make precise models of physical structures from ferns to galaxies. Fractal geometry is a new language. Once you can speak it, you can describe the shape of a natural phenomenon.

In the field of urban planning and design, the discovery of fractal geometry also engendered a shift between the old view - that sees cities as simple, ordered structured, expressible by smooth lines and shapes, which describe their overall morphology and the disposition of their elements - toward a view that cities are complex organisms, evolving and changing according to local rules and conditions, which manifest more global order across many scales and times. Batty and Longley (1994) believe not only naturally growing cities but changes in forms and functions of planned cities over time, are in a way that make them both ideal candidates for application of fractal geometry.

3. Fractal analysis of urban morphology

In city ecosystems, the pattern of pedestrian and traffic movement, neighborhood decline, renewal, consolidation and transition will be constrained or influenced by morphological elements. Edges, boundaries, regions, coarseness, fragmentation, homogeneity or heterogeneity of neighborhood patterns are the most important features in both Landscape and urban ecology. According to the recent research, the urban feature defined by its physical elements, better represent city identity than the one defined by its underlying social elements. For example Webster (1995) argued urban environmental categories will be defined by housing density better than population density. The reason should be obvious; population density will vary to some degree between neighborhoods of the same housing density.

Fractal analysis of urban morphological elements offers a base to classify facial pattern recognition the same sort of digital technology fingerprint. It provides urban analyst a way in order to uniquely identify a particular code for an urban form or pattern. It is similar to DNA code or a fingerprint for a forensic scientist who wants to identify its owner. In the case of city, the configuration of shapes and structures will produce that morphological fingerprint.

3.1. THE METHODOLOGY

As illustrated in diagrams 1 and 2, the suggested method will substantially be able to approach the objectives addressed in this paper.

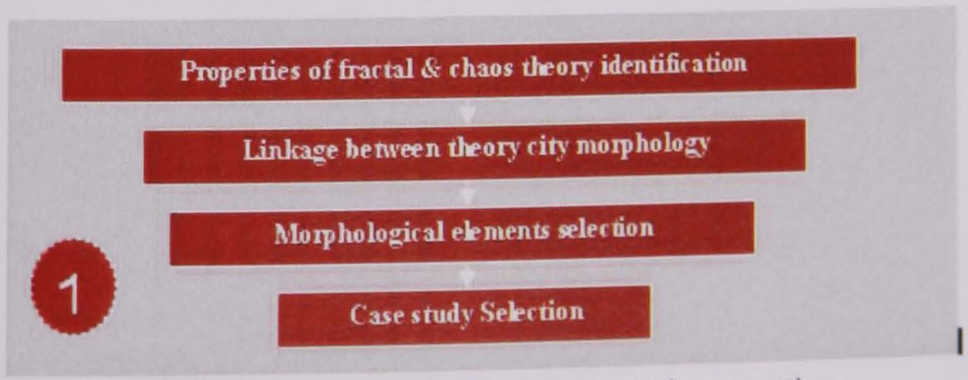


Diagram 1: Theoretical stage and case study preparation

At the theoretical stage the properties of fractal and chaos theory and their possible links with urban morphology has been reviewed. It identifies those elements of the city that lend themselves to the measurement and evaluation by employing fractal analysis software. From the information collected from this part, three different building set were selected to be tested empirically at stage II.

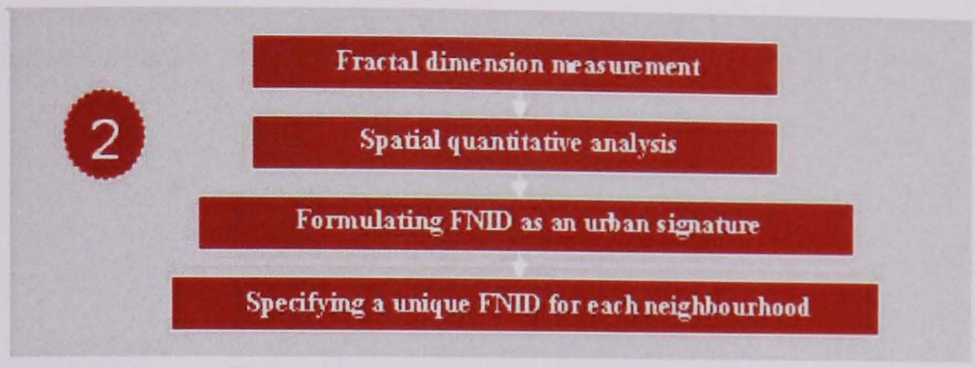


Diagram 2: Empirical stage and data analysis

At empirical stage the quantitative data collected by calculating the fractal dimension of urban forms mainly based on available air maps and street panoramic photos. Several streets of Tajrish, a district in the north of Tehran, were selected where the contradiction between traditional organic change and fast urban developments provides an appropriate case for comparison and further analysis. A morphological urban pattern surveyed, assessing fractal dimension of different urban spaces at local street level in order to specify a unique fractal signature (FNID) for each neighborhood unit.
The image based morphological analysis offers a language for articulating above idea, a range of precise measurements was undertaken to record distinctive forms in order to parameterize those measures. Image texture measures will present fine discriminations of city features that are defined in terms of built or natural environmental elements.

3.2. TEHRAN AS A CASE STUDY:

The morphology of Tehran, the capital of Iran, is the product two different pattern of growth, on one hand a fast and huge expansion of the former city towards its suburbs and on the other hand a gradual organic growth of the villages which were around the city in the past but they are now inside the city (Figure 1).

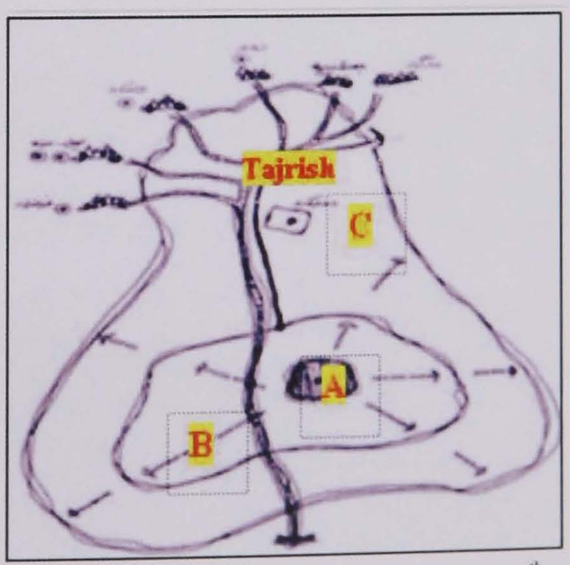


Figure 1: the sketch shows Tehran expansion in 20th century.
A) City boundary in 1890 B) City boundary in 1940
C) City boundary in 2002

The City of Tehran has experienced the destruction of its past visual order and harmony by new and modern developments during the last century that caused this city to lose their pre-modern identity. The modern pattern of the new constructions is diametrically opposed to old patterns evolved during gradual organic process. Tajrish located in the north of Tehran is a good case manifested the contradiction between both patterns of growth.

As illustrated in figure 2 and 3, a similar pattern originated from previous organic growth, obviously exists in the urban fabric in Tajrish repeated at different scale and size. This similar unit could be considered as a cell generator, creating the site morphological pattern. As shown in figure 3, this proportional structured pattern was constructed by a self-similar semi-square shape, repeated at different scale and size in this area. Figure 4 abstractly highlights the existence of the underlying geometrical order within neighborhood units, demonstrating fractal characteristics of urban structure in Tajrish. This preliminary evidence reveals the potentiality of chaos theory and fractal geometry application in urban spatial analysis.

Figure2: Map of Tajrish located in the north of Tehran

Figure 3: Similar pattern originated from organic urban growth exists at different scale and size of Tajrish urban structure.

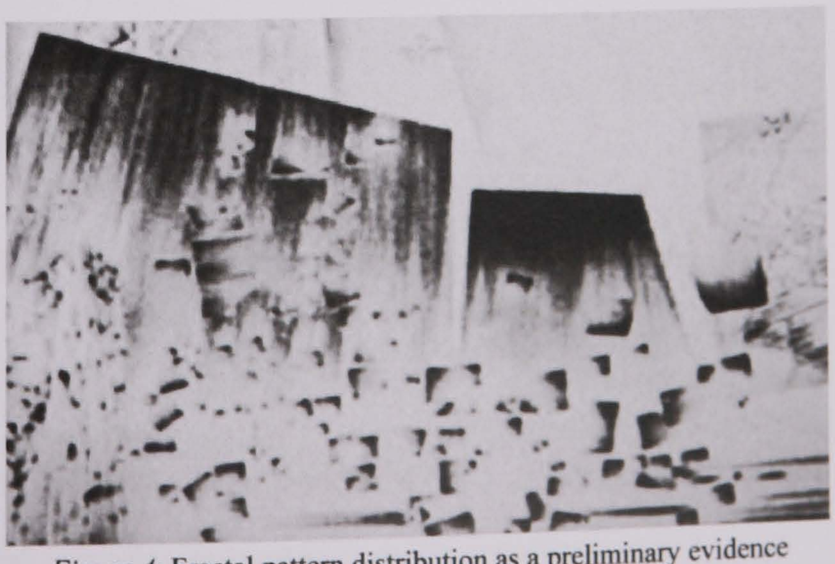


Figure 4: Fractal pattern distribution as a preliminary evidence of Fractal characteristics of urban structure in Tajrish.

3.3. FRACTAL CALCULATION

There are several calculation methods for measuring the fractal dimension of the environment; all of them often follow a simple logarithmic equation based on a power law relationship between the numbers of elements exist in different scale of an object.

$$D = \log N \times \left(\log S^{-1}\right)^{-1}$$

D: Fractal Dimension, N: Number of elements countable at specific scale, S: Respective Scale of an object

A Fractal software employed here facilitates the calculation. The data presented in this paper is mainly based on the box counting method and Richardson walk method. These two Methods among other ways of fractal calculation have been fully explained by Mandelbrot (1982), Bovill (1996), Kaye (1889), Cooper (2000) …

Batty and Longley (1994) applied fractal analysis for measuring the level of complexity exists in the boundary of Cardiff and compare it with some other cities around the world. Table 1 contains some their result.

Table 1: Fractal dimension of some cities' boundary

City Name	Year	Fractal Dimension
Tokyo	1960	1.312
New York	1960	1.710
Paris	1981	1.66
Cardiff	1981	1.586
London	1962	1.774

It was examined for the case of Tehran and the result has been summarized in Table 2.

Table 2: Fractal dimension of Tehran boundary from 1820 to 1992

City Name	Year	Fractal Dimension
Tehran	1820	1.322
Tehran	1860	1.435
Tehran	1900	1.495
Tehran	1914	1.553
Tehran	1939	1.412
Tehran	1962	1.575
Tehran	1970	1.625
Tehran	1992	1.762

This method could be applied for other urban features such as, city networks, skylines, density of built up area, the degree of open space, Landmark distribution, etc. Any one of these urban elements in combination with the others will assist us to develop the fingerprint idea.

3.4. FRACTAL NEIGHBORHOOD IDENTIFICATION CODE (FNID)

Since the new view observed cities as a live organism, some of recent urban scientists have made an attempt to identify a kind of DNA or textural signatures for urban neighborhoods (Webster, 1995). This paper suggests a method to develop the fingerprint idea in term of FNID by which every neighborhood might be morphologically typified. One of the important morphological features that have been addressed here is the degree of building fragmentation by comparing built up areas to open space within urban structures.

Benoit software, a fractal calculator, was employed in this research to facilitate the fractal measurement of urban environments. The inputs are the BMP image format of the maps of the case study in different scales and the soft ware counts the number pixels or the elements out that image. Then a sequence of logarithmic calculations will define the fractal dimensions at different scale. Figure 5, is a plot the number of occupied pixels, as representatives of built up area, and table 3 contains F(b), Fractal dimension by box counting method, resulted from each time calculation.

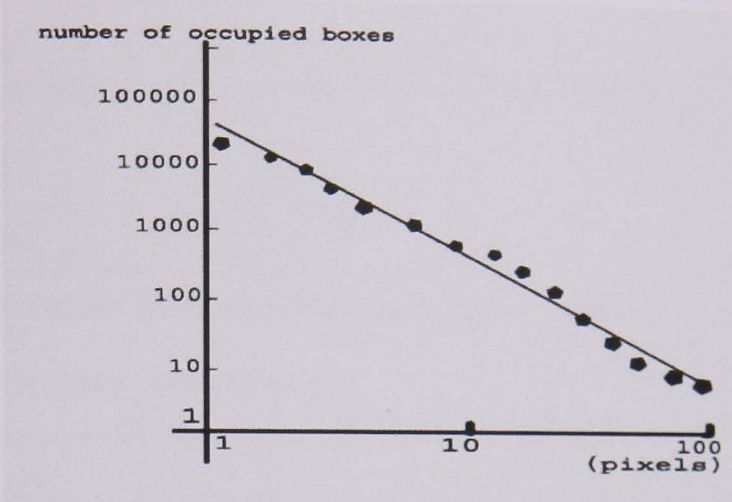
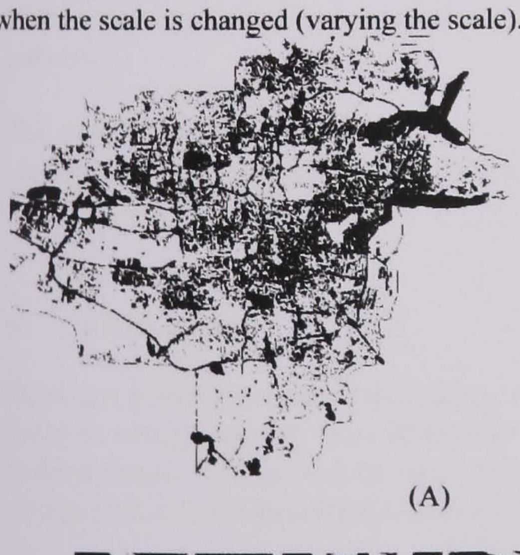


Figure 5: Number of occupied built up area in Tehran map calculated in box counting method

Table3: Estimating the fractal dimension of Tehran by fixing the scale and varying the size

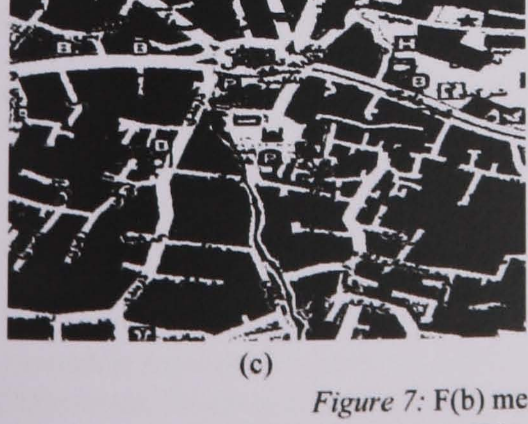
Box size (pixels)	100	75	50	35	20	10	5	1
F(b)	1.484	1.592	1.701	1.769	1.791	1.812	1.693	1.652

As shown in above table the F(b) is changed when the measurement employs smaller box units (varying the size). The software calculates the average of these as the outcome which in this case would be 1.691 for whole Tehran. In the same way we are be able to measure F(b) for each district of Tehran at different scale. Figure 7 demonstrates the result when the scale is changed (varying the scale).

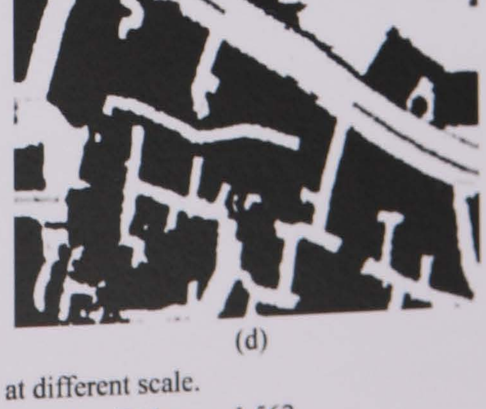


(A)

(B)



(c)



(d)

Figure 7: F(b) measured for Tehran at different scale.

A) Whole Tehran = 1.691 B) Shemiran, the north of Tehran = 1.562

C) Tajrish = 1.630 D) one of neighborhoods in Tajrish = 1.806

The following code created by the sequence of fractal measurement, might be considered as a unique mathematical neighborhood ID.

A = 1.691 B = 1.562 C = 1.630 D = 1.806

As the fractal dimensions at different scales vary between 1.00 and 2.00, therefore the decimal numbers are defined as FNID.

A - B - C - D

691	562	630	806

The results for 12 neighborhoods within the case study are summarized in table 4.

Table 4: FNID measured for 12 neighborhoods in Tajrish

Neighborhoods	N1	N2	N3	N4	N5	N6
FNID	691-562-630-806	691-562-630-791	691-562-630-720	691-562-630-601	691-562-630-582	691-562-630-757

Neighborhoods	N7	N8	N9	N10	N11	N12
FNID	691-562-643-672	691-562-643-741	691-562-630-639	691-562-630-803	691-562-630-598	691-562-756-760

As it is obvious in table 4, FNID is contained 12 numbers in 4 sections, A-B-C-D. Respectively each part demonstrates, City ID (A), District ID (B), Local ID (C) and Neighborhood ID (D). As shown in the table in most cases in Tajrish area 9 numbers out of 12 are stable. FNID for N7, N8 and N9 show the change In their local ID, in another words this implies these urban units are not belongs to the same local area as the others. The similarities and the differences in FNID assist us to classify the neighborhoods in a city and draw a new district plan based on morphological urban patterns.

The table also shows Neighborhood ID (D section), changes within a range of 582 to 806, this can be used as a controlling tool, to constrain urban new developments within certain range of fractal dimensions. This will arguably provides an effective way to conserve urban qualities by more accurate method.

4. Conclusion

There is a growing number of evidence to support the application of these theories, However, the evidence exists it is based on either large city wide scale, such as work by M. Batty and P. Longely or very detailed level of individual building design, such as work by Jencks and C. Bovill. The method suggested here, intends to fill the gap by examining the application of the theories at local level of the city (neighborhood scale).

Some outcomes of this method would be:

1. The paper suggests a more appropriate method to analyze and criticize urban forms and spaces in the light of chaos theory and fractal geometry.
2. The process of urban change at macro scale can be more relevant and sensitive by understanding the process of change occurs at micro scale (local level) of a city.
3. Fractal analysis of urban environment indicates a strong relationship between fractal dimension and characteristics of urban pattern by which different urban areas can be distinguished and typified.
4. In some parts of the city, where the fractality (fractal dimension) of their hierarchical structures the same; more visual order and harmonic urban space would be expected.

More research is required to explore the possible relationship between the visual perception of urban forms and their fractal dimensions. However, the same process of fractal assessment of urban patterns introduced in this paper could be applied for measuring other urban features such as, skylines, street vistas, street elevations, street edges, etc where a combination of all will introduce the FNID idea as a more effective urban spatial analysis tool.

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