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.