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Research

Can Chaos Theory Explain Complexity In Urban Fabric? Applications in Traditional Muslim Settlements

Abstract. The present work is a limited analysis of the traditional urban fabric of Muslim cities in the light of this theory. Chaos theory provides better instruments for the analysis and understanding of the traditional urban fabric in old Muslim cities that have, paradoxically, long been considered as lacking order and thus “chaotic” in the pejorative sense! Beyond the analysis, our study also aims at providing a fresh approach to the built environment that shifts the architectural and planning professions from the traditional design and planning approach to a self-generating process that, once set up, would function and develop without need for intervention. However, the present study will be limited to the application of such concepts at two levels. At the urban level, it will provide evidence of the existence of chaos and fractals at the scale of the city. At the domestic level, concepts are applied to housing evolution and community spaces.

Introduction

Despite the increasing interest of scientists from various fields of physical, natural and human sciences in chaos theory, its application in urbanism and in architecture seems to be still in an early stage. Among its earliest applications in architecture and urbanism are those of Batty [1990, 1994], Bechhoefer and Bovill [1994, 1996], Bechhoefer and Appleby [1997] and Salingaros [2003]. In a further step, Crompton [2001] attempted to use the fractal dimension in measuring the complexity of the dwelling space through the counting of the number of places it offers to users in an indoor space. However, in most of these studies the mathematical instruments seem to overwhelm the new approach and thus limit the scope of architects and planners to explore it in both analyzing the built environment complexity and in adopting it in their practice, a fact that was also noticed by Ostwald [2001: 79] and Mulligan [1997]. In contrast to the pessimistic standpoint of Ostwald [2001] announcing the death of fractal architecture in the late twentieth century, this paper presents the thesis that “chaos and fractals” is a dormant theory and has hidden potential that is still valid for exploration. Since its beginnings, it has been abused by architects, initially to justify their bizarre forms, then to legitimize their irrational actions [Salingaros 2006; Ostwald 2001]. To date it is still misused by considering it as a design fashion. The latter approach, mostly based on aesthetic considerations, results in rigid forms and elevations that show some characteristics of fractals and complexity but which nevertheless clash with the essence of the theory, which aims at reinstating the natural dynamics of reality in architecture and urbanism.

Application to traditional Muslim cities

The present work is a limited analysis of the traditional urban fabric of Muslim cities in the light of this theory. Chaos theory provides better instruments for the analysis and understanding of the traditional urban fabric in old Muslim cities that have, paradoxically, long been considered as lacking order and thus “chaotic” in the pejorative sense!

Beyond the analysis, our study also aims at providing a fresh approach to the built environment that shifts the architectural and planning professions from the traditional design and planning approach to a self-generating process that, once set up, would function and develop without need for intervention.

Chaos and fractal theory relies on a series of concepts that establish its structure and define its methodology and techniques. Among the concepts that are directly linked to the physical environment are growth and self-similarity, randomness and unpredictability, dynamism and non-linearity, order and disorder.

When considered in light of this theory, the city has many scales, from the largest regional scale down to the scale of the geometric pattern of ornaments [Batty 1994; Salinger 2006, 2007]. However, the present study will be limited to the application of such concepts at two levels. At the urban level, it will provide evidence of the existence of chaos and fractals at the scale of the city. At the domestic level, concepts are applied to housing evolution and community spaces.

Chaos: from disorder to a highly hidden order

Most of the studies on Muslim cities were initiated by Western scholars during the nineteenth century as a result of Western colonial expansion to overseas and the spirit of exploration that characterised European intellectual life. The extensive field and theoretical research undertaken, although mostly objective scientifically, was paradoxically motivated by the military and political agendas of the colonial powers. Thus many value judgments spoiled the results of the research and generated skepticism in later generation of non-Western scholars [Said 1979]. Two of the sources of these misjudgments were the glorification of early culture and reference to the Greco-Roman model of cities. The Western scholars' approach, already distorted by the effect of superiority and the reference to Greeks and Roman legacy of planned towns, projected the Muslim cities on a background that was significantly shaped by Cartesian geometry. A pattern of streets following straight lines and right angles, reflecting the principle of orthogonal grid organised around the *Cardo-Decumanus* axes, was thus considered as the golden rule for measuring the degree of clarity and order in other non-Western cities [Morris 1994: 55-59; Sauvaget 1949; Eglash 1999: 3]. The complex urban fabrics of Muslim cities was inevitably considered to be a reflection of disorder. This disorder was then explained at the cultural, social and political levels as a sign of absence of citizenship in the Muslim societies, and lack of administrative and political institutions [Sauvaget 1949; Marcais 1957; Letourneau 1985].

According to Batty [1994: 12], this view was not limited to a few non-Western scholars, but generally characterised the philosophy of the nineteenth century, based on the mechanistic knowledge, Euclidean geometry and reductionism which together formed the cornerstone of the new sciences. Often the norm was to impose the geometry of the straight line on forms that clearly did not meet such geometrical purity in reality [Batty 1994: 19].

This approach continued to shape our present cities through the domination of perfect geometry on urban planning and architecture. Irregularity of form conflicts with architects' and planners' intuition and predisposition to think in terms of the simplistic geometrical order based on the geometry of Euclid and the Greeks [Batty 1994: 8].

It is only recently that irregularity in geometry is considered as a sign of complexity and richness rather than as simply a lack of order. Organic cities, mainly characterized by their irregular geometry, are cities whose morphology is governed by a deep underlying structure.

Chaos theory, also known as the science of complexity, provides efficient instruments for uncovering this underlying structure. Irregularity should therefore be analysed as the result of a set of rules that governed the successive physical events that gave shape to the city, which accrued in layers over time. The factor of time, that is the age of the city, is thus present in its morphology through the intensity of events and defines the degree of urban complexity.

Chaos applied to Muslim cities

Initially, Muslim cities could be classified into four main categories. The first category is religious (Makka, Medina, Jerusalem). The second is royal (the Round City of Baghdad in Iraq, Al-Zahra in Muslim Spain). The third is inherited (Damascus, Aleppo, Cherchell in Algeria). The fourth is spontaneous (the case of most other cities). The religious and the spontaneous ones generally develop as a natural consequence of the physical conditions of site and the small actions of settlers in the absence of any top-down planning, while the second ones are generally shaped as a consequence of a political motivation for their foundation. Most often the structure of the latter is highly defined by a simple and clear geometry. The Round City of Baghdad, founded by the Abbasid caliph A. J. Al-Mansoor in 764, is a case in point [Ben-Hamouche 2004] (fig. 1).

Fig. 1. The Round City of Baghdad, showing the strong geometric pattern.
Drawing by the author

Regarding the third category, inherited cities, due to historical and geographic circumstances, many Roman cities were inherited by Muslim conquerors and thus were subjected to many transformations. Their initial grid layer gradually disappeared under the irregular geometry of an incremental development process.

Regardless of their origin, in the long run urban fabric acquires a high level of complexity in which the initial urban form is turned into a pale background for later development. By stripping back successive layers, we can infer that during their foundation and early stage of development, they were relatively simple and had a certain geometric clarity. Over centuries, they ended up with a complex urban fabric characterised by a high degree of interlocking of buildings, a variety of architectural details, and an irregularity of street patterns. The Euclidean geometry that might have explained their initial forms can no longer provide instruments to deconstruct their present complexity. The theory of chaos and fractals, that is, the mathematical and geometrical study of irregularity, provides an alternative theoretical framework for the analysis of this complexity [Bovill 1996b: 3].

Examples of Muslim cities

Damascus and Aleppo provide good examples for the distinction between the two types of geometry and the evolution from a previous to the later one. The grid pattern of road networks that were established during the Hellenistic era dominated the initial urban tissue. After the Islamic conquest, the city structure was gradually transformed into narrow winding streets, dead-end alleys, and interlocking buildings. In reconstructing the old urban fabric, Sauvaget [1949], who might have been highly influenced by the French mathematicians' rigour, explained the radical transformations as a consequence of change in the institutional system, and lack of control. In other words, it was interpreted as being due to an absence of order.

In the light of chaos and fractal theory, the initial Euclidean geometry, imposed by the strong politico-military power of Romans, was substituted by the myriad of individual decisions at a much smaller scale that generated a fractal geometry and reflected the reality of daily life [Batty 1994: 8].

The strong grid that characterised the initial layout of Damascus and Aleppo did not prevent these cities, after centuries of development, from hosting complexity and thus becoming similar to the other cities such as Baghdad, Cairo or Algiers.

However, time is a major factor in defining the "maturity" of a city and determining its degree of complexity. An older city is always a recipient of many physical events and accretions that have piled up over each other. Its "fractal dimension", even without mathematical calculations, could be measured by its age, which goes back to its date of foundation. For instance, Manama and Muharraq both emerged in 1780s, and are very young if compared with Cairo (950 A.D.), Baghdad (764 A.D.) and Tunis (7th century A.D.). Inversely, we would expect to find that Medina (622 A.D.) and Mecca (2000 B.C.) are more complex than any other cities (fig. 2).

Fig. 2. A portion of Manama city, Bahrain, in 1950s showing the low intensity of urban space usage compared with older Muslim cities.
Source: Directorate of Survey, Bahrain

The evolution of the city of Kufa, founded in 637 AD, is another example of the divergence between the two types of geometry. Despite the absence of initial plans, there is an account that gives us the details of its foundation. Describing the process of its layout, historians state that a centre was first established as a square that was defined according to the shot of an arrow to the four horizons, that is, approximately equal to 480x480m [Al-Tabari 1963; Aal-Mawardi 1960; Jait 1986]. In a second stage, roads were laid out according to a set of norms that were ordered by the supreme ruler, the Caliph [Al-Tabari: II, 17]. Accordingly, main roads (*manahij*) were to be forty cubits; those following the main roads, thirty cubits; those in between, twenty; finally, lanes (*aziqqah*), seven. Planning units called *khitar* (plural of *khitta*), to be developed as residential quarters, were also defined within this road network. In describing the development process, historians did not mention any intervention of the ruler in organising these units. As part of the collective property of tribes, it seems that these plots were subdivided among members of tribes and

developed solely by individuals. Thus construction would have been carried out in an incremental process. It can therefore be deduced that the city layout initially had a Euclidean geometry based on the road network and the central square. However, this geometry would have been modified gradually through the incremental process comprising the private and collective actions into a fractal geometry.

Two aspects of fractal geometry could be made evident in this process. The first concerns the road layout. A tree-like pattern of roads in a hierarchic graduation of four levels from the main arteries to the narrow streets has been established. Two other levels that consist of semi-private and private paths often occur over time. Blocks that are developed out of the urban *khitat* units often comprise winding streets and dead-end alleys. In some cases, dead-ends emerge in response to the need to provide access to deeper shares within the residential block after subdivision into smaller shares. In other cases, they are formed from the blocking of one end of a semi-private street and the addition of an arch or a gate, an action that is often undertaken by neighbours for reasons of security and privacy. This might explain the high percentage of dead-end streets that characterises old Muslim cities, ranging from 25% to 45% of the total network [Raymond 1985].

In fractal jargon, this process could be simulated by the continuous iterative process of generating lines. The main roads initially laid could be considered as the “active lines” [Eglash 1999: 16]. Soon they become “passive lines” through the steps of replacement. Theoretically, this process can continue endlessly. However, in the case of the urban space in old Muslim cities, it might end after the sixth or seventh steps of the down-scaling process, which correspond to thresholds of houses and rooms. This process is explained in fig. 3.

Fig. 3. The generation of road pattern adapted to Cantor's model of fractals

The geometry of the main roads was also subjected to a continuous process of reshaping though the encroachment of private houses on public space. Despite the *Hisba*, which permanently controlled all public spaces and buildings for the purpose of removing objects that obstructed the flow of traffic, high overhead projections and extra steps in front of doors were often permitted or passed unnoticed, and thus increased the fractal shape of the roadsides. The osmosis-like relationship between the *Muhtassib* and the proprietors of houses along main roads thus dictated the irregular landscape of the roads and generated their urban architecture (fig. 4).

Fig. 4. Street form shaped by the osmosis-like relationships between the flow of traffic and individuals' encroachments

Fig. 5. Application of the Cantor principle to action in the built environment

The sections that follow will describe the sources of complexity in traditional Muslim cities, based on the Islamic principles that govern the actions of the individuals and the communities.

Sources of complexity in traditional Muslim cities: norms and behavioural standards

Complexity in Muslim cities results from the incremental process of development and the slow urban growth that develops out of small actions. Two interacting factors constitute this process: the time factor – i.e., development occurring in successive stages – ; and the intensity of individual actions in the space. This seems to be the origin of any other so-called spontaneous, natural and unplanned developments that generate urban fabric in the absence of official interventions, voluntary design, or the guidance of professionals [Batty 1994: 8]. However, in Islamic cities the process was ruled by a set of endogenous norms and behavioural standards that stemmed from the symbiosis between Islamic jurisprudence and the specific conditions of each location. Unwritten codes that structured this generative process were thus established in each region and city [Hakim 1994, 2007a, 2007b]. Fig. 5 presents the model for fractal generation adapted to the individual actions on the built environment, a process that will be examined further at the end of this study.

We will now elucidate some of these codes that generated complexity and thus help decompose the fractal geometry underlying the traditional urban fabric in old Muslim cities. Since housing forms the largest part of the city space, the analysis will be limited to the domestic scale ranging between the neighbourhood and the housing units.

Fig. 6. Portions of urban fabric. a, above) in Muharraq, Bahrain showing the mass-void ratio and the different plots forms; b, right) in Tunis, showing the variation of houses at a more detailed level. In spite of the difference of locations, they show a striking resemblance due the similarity of “the rules of the game”

Private legal power

Private legal power is called *Wilaya*, an Arabic legal term that connotes the freedom to act on one's property without the consent of any outside party. In Islamic jurisprudence, a person in full possession of his mental and physical capacities has the right to act on his own property without need for permission from the ruler. For instance, a person has a right to open a door, seal a window, add a partition wall, relocate an entrance door as long as no damage is caused to neighbours or to the public. This is the code behind the large freedom of action that people in traditional Muslim cities enjoyed and that was the source of the uninterrupted flow of small actions. Over time, these small actions generated a cascade of details and a fractal geometry that could be seen in the form of urban fabric (figs. 6a, b).

A principle of reclamation of un-owned or dead land constitutes a large margin of freedom to individuals. The majority of Muslim jurists agree that a person could reclaim this type of land through building, farming and any other action without referring to the authorities. This applies mostly to vacant land that is far from urban concentrations. However, unused spaces within the cities such as "overhead air" in the streets that is beyond the height of passers-by is also considered as dead space, a fact that gave rise to the projections and arches-like rooms over streets.

Agreements and right of precedence

As an extension of private legal power, inhabitants and neighbours in traditional settlements had the right to establish different agreements among themselves regarding the mutual use of their properties and exchanges of rights. For example, a person could sell part of his wall, or rent a right of support or a passage to his neighbour for a defined period of time. Most of these agreements were verbal and were established in the presence of other neighbours as witnesses. They were also transmitted orally from fathers to sons over centuries.

The right of precedence meant that the rights of any pre-existing buildings on the site prevailed over those of buildings built later. In developing their plots or undertaking a new action, proprietors either had to consider the existing ones in terms of privacy, shade, wind, etc., or to establish agreements to overcome the constraints on his action. When positioning a window or an entrance in his new construction, a proprietor had to avoid placing them opposite the pre-existing ones of the neighbours facing him. In this sense, any new action becomes a problem-solving process involving a set of pre-existing constraints. Therefore, over time agreements and rights of precedence became accumulated conditions that generated specific constructive and architectural solutions and thus further generated fractals.

Inheritance law

In Islamic law, heirs are classified into categories according to their kinship and sex. Basic shares stated in the Qur'an are as follows: $1/2$, $1/4$, $1/8$, $1/3$, $2/3$, and $1/6$. For instance, the property of a dead man who left a wife, two girls and a boy should be subdivided so as to give one-eighth of the property to the wife, and the remaining seven-eighths to the children. Since a boy is entitled to twice the share of a girl, the remaining property will be subdivided into three parts, with the boy having one-half (that is, $7/16$ of the whole property) while the girls will have one-fourth each (that is, $7/32$ of the whole). Following the death of the original heirs, the same process will apply on each of the shares depending on the number of descendants of each heir.

Fig. 7a. hypothetical process of land subdivision according to Islamic law

Fig. 7b. The impact of land subdivision according to Islamic law on the urban fabric of Algiers

Within a century, the same initial property might undergo up to three subdivisions, resulting in a cascade of small functional shares of urban spaces.

Describing the Islamic law of inheritance, Brugman [1979: 88] states that it “is characterised by an excessive fragmentation of the estate”. However, jurists placed conditions on the subdivision process that preserved the usefulness of resulting shares in terms of conditions of use, accessibility and independence. Regarding the mechanisms and rules of subdivision, Akbar [1988: 135-136] thoroughly discussed the divisibility of elements and the principles of subdivision. For instance, some elements in the estate, such as wells, small courtyards, stairs, passageways and baths, could hardly be subdivided and were thus either kept intact and used in common, or were sold entirely if that was possible.

These mechanisms of subdivision generated continuous changes in the boundaries of properties and locations of partition walls, and were thus continuously incrementing the complexity of the urban fabric and increasing the “fractal dimension” of cities. Property lines and party walls in any given block increase in number at each stage of subdivision. The older the city is, the more it contains smaller shares, and shorter and irregular lines, and thus the more fractal it becomes (fig. 7).

Pre-emption

Pre-emption is the priority given to the co-owner in a shared property to substitute himself for an outsider purchaser, if the other co-owner decides to sell his or her share, in other words, the right of objection. According to this principle, shareholders in a collective property that could not be subdivided have the right to prevent each other from selling their shares to an outsider. This principle had the opposite effect of the subdivision that results from inheritance law, in that it permits the reunification of the smaller parts into a new, larger property. Further, if there is a large number of co-owners, the right of pre-emption is granted to all of them, even if their shares were different. In this case, the share that was to have been sold is to be further subdivided wisely and equally among partners who wish to avail themselves of their right of pre-emption, provided that this is feasible.

Scholars of different schools of Islamic law have diverging points of view regarding the extent of this principle. According to the *Hanafi* school of law, this principle could be applied even to neighbours. Based on the theory of prejudice, the right of pre-emption was granted gradually to the full partner, then to the partial associate(s) who shared some services such as an entrance, or a passage, and finally to the neighbor who has an adjacent property or lives in a same lane. If all those with the right of pre-emption resigned, the right could be granted to the back neighbour, who might have an entrance in another lane, and shared a back partition wall with the property to be sold. In the absence of the legal process, this right is often conceded to neighbours in order to maintain good relationships. In physical terms, the principle of pre-emption unified fragments of an earlier property in new plots and thus generated greater complexity in the geometry of the block. In case of two houses on opposite sides of a street, they can be joined by an overhead room or bridge-like passage that maintains fluidity of circulation yet allows connection between the two houses (fig. 8).

The principles discussed above do not form an exhaustive list, but are only examples. Many similar codes that have a direct impact on the generation of “fractality” could be established through an exhaustive study of Islamic law.

Complexity and “fractality” in old urban fabric were the result not only of these principles acting separately, but also simultaneously and in parallel. Consequently, transformations of the site took the form of a sedimentation of successive layers of actions and changes effected by inhabitants over time. Therefore, the older the urban fabric, the more complex its geometry.

Fig. 8. A street in Casbah, Old Algiers, showing an overhead projection linking two opposite houses

The language of chaos and fractals applied to Muslim cities

It is not possible to dissociate chaos and fractals. Due to their interaction, they are either stated together [Crilly et al. 1990; Strogatz 2001], or somewhat interchangeably [Gleick 1988]. For instance, according to Kenkel [1996] the fractal dimension can be viewed as a relative measure of complexity, and thus of chaos, while fractals are presented as part of chaos theory [Gleick 1988].

Literally speaking, chaos is a broad term for indicating the science of complexity. It applies to natural sciences such as physics and biology, as well as to human sciences such as economy and sociology, whereas fractals are limited to the geometry that is concerned with the application of non-Euclidean analysis, measurements and calculations to complex objects. The two terms are thus used together to explain complexity in real life and describe the inherent irregularity of natural objects.

The “theory” of chaos and fractals has been described as a collection of examples, linked by a common point of view. Its properties are not formally defined and it is thus not an organized theory [Lorimer, Haight and Leary 1994]. Eglash [1999] defined some of the

essential properties, which are recursion, scaling, self-similarity, infinity and fractal dimension.

Now we will select some of the key properties and verify their presence in the urban fabrics in traditional Muslim cities.

Growth and self-similarity

According to chaos theory, growth is not merely an increase in size, or a zooming out of a body to another scale. Rather, it is an exponential multiplication, or reduction, within the system and a successive passage from one scale of complexity to another. Zygotes are not merely scaled down human beings, and the process of ontogenetic development is far more interesting than mere enlargement [Gleick 1988: 115].

One of the first models for grasping growth was the experiment of measuring the exact length of Britain's coastline. Mandelbrot [1967] observed that as the scale of measurement becomes smaller, the measured length of the coastline increases infinitely. Although the total area is finite inside the curve, the polygon, the boundary line of the shape itself could have an infinite length. This was also explained by the Koch curve.

In traditional housing, the principle could be applied in observing the growth stages of the old cities. For instance, the city of Algiers had a fixed area of 45 hectares within the city wall during the three centuries of the Ottoman period due to site constraints. However, it witnessed a significant variation in its population size and thus, its density grew from 50,000 people to 100,000, and then reached 150,000. At the beginning of the nineteenth century, it shrunk to 30,000 due to epidemics, economic recession and wars. Such fluctuation in population size, despite the size of the site being fixed by topographic constraints, shows the "plastic" capacity of urban space to absorb endogenous growth.

In many cases the stages of urban growth are often reflected in the shift of the cities' external walls. Ghardaïa (south of Algiers), was not extended until all of the urban space inside the city wall was entirely consumed. Suburbs outside the city wall were seen as a negative form of urban development that was often avoided because it was hard to defend in case of attack.

Self-similarity at different scales of a system is another principle of chaos theory. A self-similar object is one whose component parts resemble the whole. In growing, chaotic objects tend to reproduce themselves at different scales while maintaining the same structure at all levels of growth. Self-similarity is therefore different from sameness. It is rather a resemblance in terms of structure, as well as in the process of ontogenetic development.

This principle can be seen in three forms of traditional housing that reflected the different scales of the physical environment. At the *city level*, housing was characterised by its high degree of compactness and the predominance of areas covered by buildings over open spaces [Ben-Hamouche 2008]. Ghardaïa had only a single public space in the city that is still used as a weekly market and a daily meeting place. At the *neighbourhood level* another unique area could be found as a community space in each compound. On describing the foundation of Kufa (637AD), al-Tabari (died 926 A.D.) [1963] stated that in early times each planning unit, *khitta*, which accommodated a tribe, had an open space at its centre, called *Rahba*, used partly as a burial space, and partly as a stable for keeping

camels and other animals. Although *Rahba* are not systematically present, and though they have no standard form, they were known by local people in each neighbourhood. This is what is known as self-affinity in the absence of a total self-similarity [Batty 2004]. At the *block level*, other common spaces such as dead-end streets, winding alleys, and open common courts called *finā* were omnipresent. They were used for various purposes, such as playing spaces for children, extended areas for shops, and waiting spaces for allowing loaded animals to pass because of the narrowness of the streets. At the *domestic level*, houses in most Muslim cities were inward-looking, a miniature image of the walled city within its surroundings. Despite the geometric irregularity of the house, the courtyard (*Sahn*, *Hawsh*, *Wast ad-dar*) was often square in form and was located at the centre, and thus was a dominant element around which the other spaces evolved.

Self-similarity in traditional housing could also be observed in the growth process at different scales. Old cities were surrounded by an external wall that was successively pushed back each time an extension was needed. Old walls were demolished and replaced by roads giving the city successive ring roads. The new parts then were subjected to an incremental development process similar to that of the whole city. Radial roads connecting the city centre with the city gates ensured the connection of the new extensions to the centre. In Ghardaïa for instance, one can easily recognise the stages of growth by the number of rings, like the technique used to determine the age of trees (fig. 9).

Fig. 9. A general plan of Ghardaïa, Algeria, showing the ring-like pattern that reflects stages of the city growth. From [Didillon and Donnadiou 1977].
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One principle of urban management that was applied in most Islamic cities was that harmful activities such as tanneries and blacksmiths were placed outside the city walls. As the city expanded, they were systematically transferred out to the new outskirts. This process was analysed by Raymond [1985] in defining the stages of extension in the old Cairo city.

Growth at the neighbourhood level followed a similar pattern. In describing Fustat, now part of Cairo, al-Suyuti (died in 911H/1509 A.D.) stated that residential quarters were separated by interstitial spaces. When reinforcements arrived each tribe made room for its relatives. Thus quarters got closer to each other and roads were formed [Hathloul 1996: 40].

Similarly, incremental growth manifested itself at a smaller scale in the construction process of plots. Rooms and floors were added each time space was needed and the house was then subject to successive extensions as the family grew in size.

The city could thus be likened to a three-dimensional carpet-like volume that is continuously subdivided into smaller cubes which are in their turn perforated at their centres, a model that recalls those of Sierpinsky [Gleick 1988: 100].

Self-similarity is measured in fractal geometry through a mathematical parameter called “fractal dimension”. This parameter theoretically remains the same regardless of how much the object is magnified. It is defined as the power relation between the number of pieces and the reduction factor. $A = 1/(s)^D$. Fractal dimension “D” could thus be defined as: $D = \log(a)/\log(1/s)$ [Bovill 1994: 27].

The streams of numbers and calculations behind this equation that are mostly used by mathematicians to identify the dimension of self-similarity through the process of downscaling seem to have no practical significance for architects and planners [Ostwald 2001: 79; Mulligan 1997]. They could instead be replaced by simpler ratios such as open spaces to built areas, and openings (windows, doors) to solid walls. Even the ratio of public sector to private domain could be of interest, although this differs from one city to another. Such ratios could then be interpreted in terms of the distribution of responsibilities between the private and public sectors, responsiveness to climate conditions, land-use pattern, intensity of use, etc. However, a set of maps and plans of different scales from various cities must be used if significant and reliable results are to be achieved.

Randomness and unpredictability

Since its early times, modern science has been influenced by deterministic theories such as Newton’s laws of classical mechanics and Laplace’s mathematics. Everything in the world was believed to be determined [Cambel 1993:5] by certain conditions. No uncertainty, no chance, no choice, no freedom, and no free will were left in this world; an event was believed to be caused by certain conditions that could not possibly have led to any other outcome. For a dynamic situation this means that, given the initial conditions, the trajectories can be calculated with reasonable precision. Such thought was further confirmed by modern technology and the industrial mass-production system.

In academia, determinism was attractive not only to scientists in physics and mathematics, but to scholars in human sciences as well, such as sociology and economy, who had always struggled to develop accurate means of measuring, achieve exact results and

eliminate, as far as possible, anomalies and uncertainties. Architecture and urbanism is a case in point of such an influence. Fine representational instruments, such as sharp Chinese pens and various types of rulers and scales, have always been used to achieve a high precision in plans. The design process in housing, for instance, goes so far as to define the furniture in rooms and offices and the colours of the walls.

However, this approach has shown certain limits in coping with the increasing requirements for changes and variations. Accordingly, new approaches were developed as an antithesis of determinism. Thus randomness and unpredictability have found their way, in theory as well as in practice, to architecture and urbanism.

In traditional settlements randomness and unpredictability have always been the essential ingredients in the development of urban fabric, as most of them were, in modern terms, unplanned and/or spontaneous. Rather, their development was a direct consequence of interactions between people and their environment over the course of decades and centuries. Buildings and urban spaces were subject to continuous changes and transformations that were undertaken by users and/or owners often in the absence of intervention of public authorities and directives of professionals.

For example, randomness can be found in the variety of building types that was generated by the conditions of site, in the varying internal organisations due to family requirements, and in the successive stages of development. This variety is also found in the process of construction which was undertaken by individuals themselves through a system of mutual aid from neighbours and relatives. A similar process also takes place in the open markets as vendors adjust themselves to manage their temporary privatised space according to the rule of “first come, first served” (fig. 10).

Fig. 10. a, above) An open market in Malaysia showing the organic use of space; b, right) An old village in Saudi, showing the organic form of urban fabric made of mud brick

The curdling process developed by Mandelbrot could be of interest in this regard. It consists of producing a “fractal dust” through a randomness generator that can be simply illustrated by a coin-tossing game. A grid of nine squares, which in our case represents a site for housing, is drawn on a piece of paper. Then a coin (or a die, or a random generator) is tossed for each square in the grid, with a defined probability of survival ($1/2$, $1/3$, $2/3$). Each of the remaining squares is then subdivided into nine smaller squares and submitted

to the same game. Others are discarded. At the third stage, the smaller surviving squares are also submitted to the coin-tossing rule and so on. Ideally this procedure could be repeated to infinity, leaving a dust of points. But for practical purposes, this game could be limited to three or four stages representing different scales of housing. The probability of survival of a square could be varied in order to reflect the real conditions of a site. In other words, the probability of curdling could be increased to $2/3$, or decreased to $1/3$, according to the potentialities and/or constraints that the site presents. A similar simulation was developed by Akbar [1988: 80-81] in analysing the impact of constraints and opportunities on the development of an urban fabric. Cellular automata software has also been developed to reflect the rules of the game in city development.

In reality, the probability of curdling could be substituted by natural factors (topography, a source of water) and man-made factors (zoning conditions, building regulations) that influence the process of urbanisation and construction. These factors could also be varied according to the scale of urbanisation and the construction process. A further classification into modifying and determining factors, similar to that developed by Rapoport [1969] in his study on cross-sections of housing typology, could also be added in this regard.

The infinite number of development probabilities exemplified in the coin-tossing game could therefore be taken as an image for the magnitude of randomness and unpredictability in the evolution and growth of housing units. It also shows to what extent early conditions could shape urban development of a settlement.

Therefore, in contrast to the deterministic modern approach to housing based on deterministic planning and predictability, chaos theory provides a comprehensive theoretical framework and the instruments for the understanding of the process of the formation and growth of the traditional urban fabric in Muslim cities based on randomness and unpredictability.

Bifurcation

Unpredictability can be best understood through the principle of bifurcation. Sensitivity to early conditions in the coin-tossing game leads to considerable variation in surviving squares at later stages. In other words, the longer the game lasts, the more the cases differ from each other and from the origin in a tree-like form.

A bifurcation diagram is a mathematical tool for representing the development of complex dynamical systems from simplicity to complexity. Computation can be carried out using software to identify the critical points in the curve of changes and different stages before reaching chaos. For example, an initial case “a” of a stream initially splits into two branches, and as water moves further the two branches further bifurcate into four, and then into sixteen, etc. (fig. 11).

In traditional housing, the same phenomenon, but in an even more complex process, occurs. Plots were first subdivided according to the number of users, and were then developed according to each owner’s needs, desires and economic possibilities. Housing units were continuously extended and transformed in response to the changing needs of users. Over centuries, they reached the complexity seen in traditional cities. However, self-similarity was always maintained as a result of the endogenous cultural norms and local, verbally-transmitted know-how. Therefore, in contrast to the same inward-looking housing

typology, each house had its own characteristics regarding the position of its components, such as size of plots, entrances, configuration of staircases, courtyard size, number and form of rooms, etc.

Fig. 11. Possible phases of bifurcation

Bifurcation can also be observed in the form of road networks and their hierarchy. The formation of roads and streets in traditional urban fabric can be considered as the negative space of the built-up areas, since they were defined by the external walls of houses and the process of densification of urban space. The formation of roads was related to the movement of people between places of interest (home, markets, mosques, city gates), and the location of these places combined with the site topography. According to Ribeiro [1997: 294], Y- or T-shaped junctions in the network are of particular interest in describing these movements. “Y” junctions were generally associated with diverging from and/or converging to a place of interest in the primary network of pathways, whereas “T” junctions were associated with the intersection of primary roads and secondary networks of pathways and dead-end streets [Ribeiro 1997: 296]. While the first type denotes a moment of decision as a pedestrian chooses a preferred destination between two equal ones, the second involves a passage to another degree of circulation network that is internal to residential areas exclusively reserved to residents. “T” junctions were therefore often used as gates that were closed during night. Both types were nodes in the bifurcation diagram representing the circulation flow in the traditional urban fabric.

Dynamism, non-linearity and algorithms

Chaos theory is a new paradigm that deals with complex systems. Dynamism is the source of complexity. Dynamic systems can be natural as well as man-made, large and small, regular and irregular in shape [Cambel 1993: 2,7]. Social systems are the most dynamic systems, because they are the most powerful sources of unpredictability, uncertainty and complexity in nature and life.

In the literature of chaos theory, dynamism in complex systems is expressed in terms of causality in different states of a system. According to Young [1994: 11] causality is the probability that, given a set of factors, only that set and no other will produce the same behaviour in the system under consideration. A system in which causal connections can be defined and evolution can be predicted, is therefore called linear, whereas a system in which causal connections are uncertain and only probable is called non-linear.

Complexity in housing stems from its being simultaneously a shelter for the most complex non-linear system – that is, society – and an output of its actions. Houses are made by different hands at different times and placed next to each other in a spontaneous (but conscious) composition. Housing is therefore an outcome of a process rather than a finished product, or as it is sometimes said, it “is a verb and not a noun”. Its irregularity, variation, and randomness are the real image of complexity.

Application to housing

A standard rule for controlling complex systems is that the controlling system should be at least as complex as the system being controlled.

One of the widely used technical tools for modelling dynamic systems and expressing linearity and non-linearity is the algorithm. An algorithm is a precisely defined, step-by-step computational procedure that represents causal interconnections in a complex system. In other words, the complexity of a system is most often represented in its algorithm. The longer the string of the algorithmic program, the more complex the system.

There are many sources of complexity in housing. It stems from the multitude of actors (including users, administrators and professionals), the variety of actions (such as new projects or refurbishment, public or private projects), physical characteristics (site, climate, building materials,) and the “rules of the game” described previously.

It is beyond the scope of this paper to elaborate a comprehensive algorithm for housing. Instead, here we further explore the principles of chaos theory in an attempt to understand the urban fabric in traditional Muslim cities. Thus the algorithm technique is applied to the decision-making system in a traditional settlement that is pre-colonial Algiers, which was studied elsewhere [Ben Hamouche 1993, 2003]. The sections below will describe the steps of the two sectors, public and private, in shaping the built environment.

The public decision-making system

According to Batty [2004: 8], cities that are planned entirely or in part are usually of monumental scale, more focused and more regular, reflecting the will of the one, that is, the king or the prince, upon the many. These features also result from the mobilisation and coordination of very large quantities of resources, since this is associated with a central politico-religious power. That can be seen in the following process of decision-making in old Muslim cities:

- Step I: In legal terms, the initiation of public projects and urban development was the prerogative of the ruler. However, the technical formulation of the proposal was often assigned to master builders who were organised into a guild and headed by a trustee who was also an expert in his field. For example, in 1756 the Ottoman ruler of Algiers made a request for the provision of the city with water. On searching for a source of water, an Andalusian master builder named Sta Musa proposed the construction of an

aqueduct to catch water from Ain al-Hama spring 19 km away. A similar procedure applies to other public buildings such as the main gates of the city, the city walls, the main mosques and covered markets.

- Step II: The proposal was submitted for approval to the legal authorities. Jurists and judges investigated whether or not the project was legal in the light of Islamic law, which could be summed up in the hierarchic preservation and promotion of the five supreme Ends: Religion, Human Lives, Reason, Human Procreation, and Properties. For example, on examining the fortification of the city and its defensive system, the ruler Pasha Mustafa (1804) wished to build a fortress on a private cemetery because of its strategic location. Despite the sacredness of the cemetery, the legal council decided that defending religion and human lives was more rightful, and thus approved the project.

However, in less sensitive cases, approval of public projects was subject to the respect of rights and properties of individuals. Owners were indemnified or compensated according to the market price of their properties. The sum was estimated by experts in the field of land marketing and construction.

- Step III: The project was submitted to the treasury for investment. The public treasury, *beyt-al-mal*, was also headed by a judge who was in charge of estimating the fees and the various costs of the project. Expenses were registered in annual registers called *sijillat beyt-al-mal*, in which names of masons, their subordinate workers, and types of work performed were exhaustively listed.
- Step IV: Master-builders were finally appointed for the implementation of the project. Depending on its size and importance, the guild of builders nominated the master-masons to undertake the project. For instance, Algiers was subjected to a serious bombardment by the English officer Lord Exmouth in 1816, and an important part of the city, including the Great Mosque that was adjacent to the coast, was demolished. The guild mobilised all the masons of the city, and appealed to masons from the other nearby cities. The whole population of the city was also involved. According to al-Zahar (1781-1832), reconstruction took one month of round-the-clock work. A century earlier, this kind of construction work was carried out by slaves and prisoners who numbered, according to some estimations, about 25,000 in the city with a total population of 100,000.

The algorithm that represents these steps is linear and comprises only two lozenges from which a “one degree bifurcation” occurs. On the physical level, this is reflected in the Euclidian geometry that characterised the projects of this type. Buildings characterised by simple forms (big domes and arches) and huge scale became permanent landmarks and created an image of the city that lasted for decades and even centuries (fig. 12).

Fig. 12. a, above) the linear model of the decision-making system; b, below) a large arch in lower Casbah, Algiers, constructed during the Ottoman period (1516-1830)

Fig. 13. a, left) the nonlinear model of decision-making system reflecting the individual actions in the built environment; b, right) a portion of the urban fabric in Casbah, Algiers, during the Ottoman period (1516-1830)

The private decision-making system

The incremental process of construction is behind the complex urban fabric. Cities that grow organically developed much more slowly than those which are planned. This natural growth is due to a myriad of individual decisions at a much smaller scale mobilising smaller resources than those of the public sector [Batty 2004: 8]. On the ground, each action was a solution for a set of problems that were dictated by the pre-existing conditions of the site. The algorithm that can be drawn from this process could be organised into many “loops” that represent the principles governing the private actions previously discussed (fig. 13).

- Step I: Ascertainment of the freedom to act. An action could not take place unless the person acting was legally qualified by having the full legal power, *Wilaya tamma*. This was the case of most residents who were mature and acted on their own properties. There were three exceptions: persons with conditional power, such as the trustees acting on behalf of charitable institutions; those with partial power, such as children who did, however, own assets; and people with illegal power, such as squatters. A permission

from a legal authority for any action on properties in the hands of the person acting was requested.

- Step II: The action was examined in relation to its immediate surrounding. It could be carried out if no prejudice was caused either to neighbours and to the public, depending on the nature and location of the property under consideration. Regarding the public interest, private properties which were a source of harm, such as those generating smoke or odours, or those obstructing circulation, were generally blocked by the direct intervention of public authorities, the *Hisba*. For example, in Tunis, the judge of the city Abderrafi' (1300 A.D.) was once asked about public baths (and other similar activities) causing smoke and/or odours. He replied that unless owners managed to cope with the harm, they should be blocked [al-Rami 1995: 320].
- Step III: Objections of neighbours and associates to a private action were in most cases overcome through negotiations and agreements which led to exchanges or purchase of rights and interests, or to a friendly relinquishment. For example, a resident could purchase or rent a right for the drainage of his rain-water or sewage on his neighbour's property, or obtain it free of charge, by way of charity.
- Step IV: Pursuance of the project. In spite of the acting person's failure to establish agreements or to get relinquishment from his neighbours or associates, he nevertheless persisted in carrying out his project. At this stage such cases were taken to court. Depending on the verdict, the person acting was then either allowed to proceed or was blocked.

Compared to that of public actions, the algorithm of private actions comprises many loops which denote the spectrum of alternatives, and thus the complexity of the system. In other words, the algorithm of private actions is a non-linear system and is characterised by a high degree of bifurcation. On the physical level, this is reflected in the fractal geometry of private buildings and residential areas.

This process took place each time a building action was undertaken, however small, whether opening a window, relocating a door, or adding an upper room. Despite the limited number of "rules of the game", the final result at the urban scale over a given period of time is unpredictable, just like the coin-tossing game of squares described earlier.

This algorithm also expresses the mechanisms of self-organisation and self-renewal in traditional settlements. In most cases, private actions took place without any intervention by public authorities. Agreements, easements and/or relinquishments among neighbours and associates were established amicably and in presence of other neighbours as witnesses. Only the major cases of dispute were taken to court; these were few in number compared to the continuous flow of actions and consents. In other words, this system was based on the social balance that comes out of the conflicts of interest which urban life continuously breeds, and which generate complexity.

Conclusion

Chaos and fractals is a relatively new theory for studying complexity. It provides concepts and tools that can also be used in analysing the hidden order underlying the irregular geometry of traditional urban fabrics, which was long considered to show no order at all.

Far from comprising a mere increase in size and an enlargement of scale, the internal structure of traditional urban fabrics was characterised from the domestic level to the city level by a striking degree of self-similarity. Randomness and unpredictability explain the variety of forms and types of houses that reflected the problem-solving process of construction and the influence of early conditions of site on the overall form of the city. The technique of bifurcation explains how the houses diverged from a simple piece of land and an inward-looking common model to an infinite number of house types modelled by the variety of persons acting and their needs, and specific conditions of the site.

One way to grasp this complexity and dynamism is by establishing an algorithm for the process of users' actions that shaped the urban fabric. Two systems could be identified in this regard; the linear system and the non-linear system, representing respectively public action on one hand, and private and collective actions on the other, each of which generated a particular geometry, mostly Euclidean in the first case and fractal in the second. However, the two types interacted and came together to constitute the balanced urban fabric of traditional cities that we see today.

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