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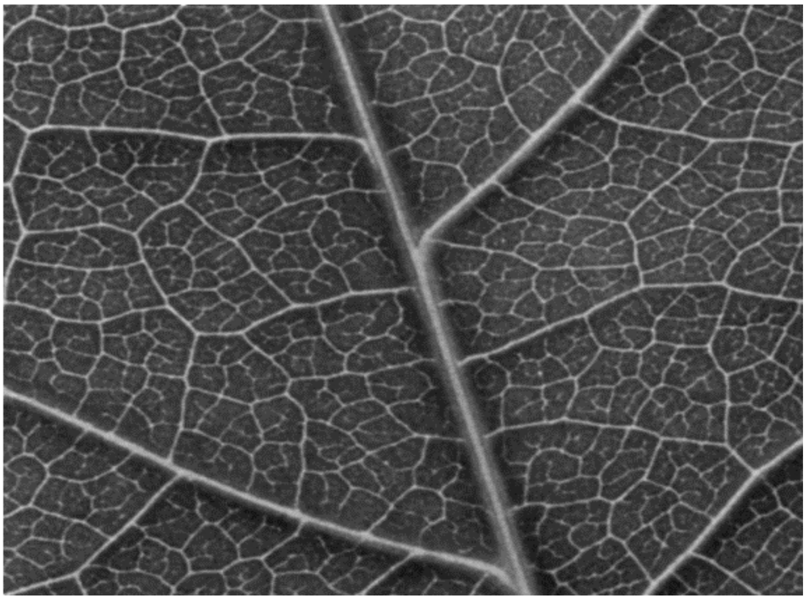

SYSTEMIC RESILIENCE OF COMPLEX URBAN SYSTEMS

ON TREES AND LEAVES

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ABSTRACT

Two key paradigms emerge out of the variety of urban forms: certain cities resemble trees, others leaves. The structural difference between a tree and a leaf is huge: one is open, the other closed. Trees are entirely disconnected on a given scale: even if two twigs are spatially close, if they do not belong to the same branch, to go from one to the other implies moving down and then up all the hierarchy of branches. Leaves on the contrary are entirely connected on intermediary scales. The veins of a leaf are disconnected on the two larger scales but entirely connected on the two or three following intermediary scales before presenting tiny tree-like structures on the finest capillary scales.

Urban system's structural resilience is highest when it is configured according to a scale free structure for its parts and for its connections. The spatial distribution and the intensity of connections in such a structure obeys a scale-free distribution. It states the frequency of an element's appearance and the span of a connection based on its hierarchic level: the smaller an element is, the more often it will be encountered in the system; the bigger an element is the rarer it will be. This fundamental law defines in itself the manner in which living organisms and things should be organized to optimize their access to energy, the use that they make of it, and their resilience. The history of urban planning has evolved from leaf-like to tree-like patterns, with a consequent loss of efficiency and resilience.

KEYWORDS:
Urban resilience, Complex systems, Scale hierarchy, Urban systemic

1 URBAN RESILIENCE THROUGHOUT HISTORY

Historical cities had the capacity to absorb successive transformations without losing their essential structure. In Paris, deemed capital of the 19th century by Walter Benjamin, no more than half of the buildings predating 1900 subsist within its historical boundaries and yet the city has managed to maintain its character thanks to the tenacious hold of the structure created by Baron Haussmann. In the historical European city, the extremely complex substrate, the subdivisions and the street grid can be traced back to the Middle Ages and sometimes even to the Roman Empire (Salat, 2011). The capacity of the city to retain its identity despite changes has vanished from the modernist city, since it has lost its distinctive character and its transformative power. The capacity to survive disasters and even to rise out of its ashes, like Lisbon after the 1755 earthquake, London after the Great Fire in 1666, Kyoto after the fires in the Middle Ages, Tokyo after the 1923 earthquake, is what we call urban resilience – a complex concept related to the permanence of a memory at once social, symbolic and material. The vast majority of historical cities is resilient and has managed to survive the centuries, often outlasting the civilizations that gave rise to them. Can modernist cities survive? Will they withstand the test of time like Rome and the great many cities that the Romans founded around the Mediterranean? Will they even manage to survive the century and hold out against the growing risks linked to climate change?

Fig. 1 Haussmannian Paris

The question is all the more important insofar as the fragility of modern cities is structural: they have exposed themselves more to risks by becoming more and more artificial and incorporating energies that are hard to predict and control. This paper aims introducing urban resilience through the prism of history and progressively shift to a more dynamic understanding of this concept, using analytical insights from complex systems theory.

2 HYBRIDIZING THE NATURAL AND THE ARTIFICIAL

In cutting themselves off from nature, cities have become fragile. Indeed, they have internalized the most destructive dynamics of nature without learning how to regulate them. If natural elements are not incorporated into the planning and construction of cities, they risk collapse.

The material metabolism of cities is founded on the redeployment of the energy of nature through the construction of hybrids. The infrastructures of modern cities combine human dynamics and natural forces in ways that transform nature and change society. This phenomenon, verifiable in all cities since the birth of the urban world five thousand years ago, has become a predominant factor in modern cities. The redeployment of the forces of nature provides the energy for processes in which complex physical hybrids (motors, telecommunications, heating, lighting, water distribution systems, air-conditioning, etc.) and complex social structures (governments, national and transnational companies, universities, etc.) are built out of simpler components. The Industrial Revolution developed such hybrids on an unprecedented scale and they relied on massive injections of energy, mainly from fossil fuels.

Massive flows of energy from nature can travel across these hybrids in catastrophic ways, breaking them down into simpler element. Indeed, in these hybrid constructions, natural forces do not lose their potential autonomy. Despite human efforts, hybrids corrode, rot, explode, etc. But there is worse. These hybrids of nature and artifice exist in a much wider context of forces over which human beings have no control, like fire or ice storms, earthquakes, and floods. Modern technological hybrids, like dams, that oppose the resistance of a human artifact to the colossal pressure of masses of water, are much more fragile in the face of natural forces than older technologies, like the floating houses in the Mekong Delta that went with the movement of the water instead of resisting it. In both cases, there is a hybridization of the natural and the artificial, but traditional technologies construct with nature, whereas modern technologies construct against nature for the purpose of harnessing its forces.

2.1 THE LAWS OF EVOLUTION

Ecology was long dominated by a paradigm of stability but now we know that all natural systems are unstable. Nature's unpredictable character is not a temporary state in the construction of human knowledge; it is a fundamental feature of nature, as theories of chaos and dynamical systems have demonstrated. Cities exist in a vortex of continually changing dynamic energy flows that we call nature. One fundamental reason for the fragility of hybrids built by human beings is that they are informed by a simple mechanical logic whereas nature is organized in a much more complex way. The fragility today comes from the coexistence of two very different levels of complexity within a single hybrid construction. Consequently the complexity of urban systems must be enhanced to approximate the complexity of natural systems.

Living systems, because they developed and became more complex over four billion years of evolution, serve as the best model for the conception of a complex system that can enduringly survive the biological conditions of our planet. Local ecosystems in particular tell us much about the optimal organization for maintaining life in a particular region of the planet. We can look at living systems to understand how to design sustainable buildings, districts, cities and regions.

Evolution permitted the survival of species through constant transformations. We can thus find a functional order in nature without an architect or planner. Adaptation via incremental changes can lead to great

transformations and great formal diversity. Evolution involves a combination of continuity and change that occurs in response to the environment. It allows us to understand why organisms differ and yet are connected over time and space (Dawkins, 1986).
Can evolutionary theories be applied to cities? Despite evident differences between the evolution of living organisms and the development of cities, there are some commonalities. Cities can be classified by type. They change over time and the types also change even as they maintain great stability. Emerging schemes, however, are never simple. The global scheme of the city emerges from its agreement with local orders. A complex order is created from the evolution of the small scale and its influence on higher scales.
The evolutionist perspective can help us understand why the crisis of cities is so profound. Never were cities confronted with such massive changes on such vast scales in so little time. Thus we may be witnessing a radical break in an evolutionary process thousands of years old and even an end to the history of cities.

2.2 THE PERSISTENCE OF THE IDEA OF A CITY ACROSS THE METAMORPHOSES OF ITS FORMS

Cities are the physical human creations that have persisted over the longest period of time, more than two thousand years insofar as the Greek and Roman cities are concerned. The historical city was a “standard ideal” but never the sterile repetition of a model. Cities of Roman origin share certain qualities and elements that derive from common principles rather than from a rigid preconceived plan. Historical cities were changing organisms, all different. Over time, the city grew and became more complex in its own right. It came to incorporate conscious and unconscious memories, traces of forgotten rituals and forms along with original patterns that remained embedded in its construction. The destruction of its memory is the worst crime that can be committed against a city. To deprive a city of its memory is to destroy its identity and its singularity, to shatter the distinctive lines of its development, and eradicate its identity and its values. “The city of Florence is a concrete reality,” writes Aldo Rossi. “But the memory of Florence and its image are loaded with values that reflect other experiences. In addition, the universal value of its experience can never completely explain that special something that makes Florence Florence.” (Rossi, 1981)
By replacing the organic morphogenesis of cities by normative plans abstractly projected onto areas relieved of the weight of culture and history, Le Corbusier’s modernism replaced the infinite variety of the human world with the serial character of mechanical production. Normative processes did not form historical cities. They are not the static product of such rational plans as Lucio Costa’s for Brasilia. They are the outgrowth of creative evolution.
Time, temporality, and duration – all have a decisive impact. We have forgotten the virtues of a slow pace. The long term and the gradual spread of information in a fragmented world created the diversity of Western cities. A rich mantle of cities with complex patterns covered both sides of the Mediterranean at a time when centralized China had already developed a more homogenous urban system. In contrast to the European complexity and variety, the city patterns of urban America, which were planned at a time when information spread more rapidly, are more homogenous, ordered as they are by an omnipresent obsession with grids. One cannot simply opt for uniformity or variety as a matter of choices in urban design; they are the product of political centralization versus fragmentation, and cultural homogeneity versus diversity.
However, no matter how many different forms a city went through, its initial founding phase will be the most tenacious attribute of its morphology. Take a city like Bath in England. The street plans laid down by the Romans at the time of its foundation have survived thousands of years, despite periods of destruction and

adversity. And even though the buildings of Turin today reflect the Baroque designs of the Piedmont kings, its inhabitants are still walking in the footsteps of the Romans on the same streets.

The cities of Magna Græcia are still standing around the Mediterranean. The mosques of Istanbul took over the great concave spaces of Byzantine churches. Nation-states pass while cities remain. “Soon you will have forgotten the world and soon the world will have forgotten you,” Marcus Aurelius famously remarked but his Rome is still present in Fellini’s Rome. And although Rome may be eternal, who believes in the eternity of Italy? (Vance, 1990)

But is this still true today? Satellite images show us the inexorable dilution of the form of cities. At what point will the age-old balance of Dutch cities, as Vermeer and Peter de Hooch knew them, be destroyed by the massive emergence of the conurbation of Randstad? The slab blocks of the modern housing projects can be seen from the tower of Delft’s Neue Kerke and Vermeer’s famous view of Delft, still visible only fifteen years ago, is now disfigured.

2.3 MORPHOGENESIS AND EVOLUTION

Cities have changed more in the past twenty years than they had in two thousand years before. Their evolution can be described in ten processes:

1. Phases of evolution are connected more to the functional life of the city than to chronological time.
2. Even though the city changes over time, certain physical features like the network of streets or the urban fabric are remarkably unchanging. The city can be deformed, sometimes impoverished like the center of Boston, but without ever totally shedding its past. This is why the blank slate approach to urban planning that destroys the city or razes whole districts brutally interrupts and damages the city’s evolution.
3. Whereas forms tend to persist, functions change.
4. The capacity to have different successive functions fulfilled by the same forms or by gradually modified forms is the adaptation that characterizes historical cities.
5. The adaptation is not only a matter of the city’s physical structures. It is a process of continually adjusting form and function – a matter of mutual transformation rather than the primacy of functions over forms. The fundamental persistence of adaptation is the basis of the evolution and continuity of cities.
6. Throughout history cities have spread out in continuous processes in which changes of scale and size gave rise to integrated wholes. After the Second World War, modernism caused an explosion of the urban form and huge breaks in scale before the phenomenon of urban sprawl came to dilute the form and dissolve the scale in endless repetition.
7. Morphological dynamism was one of the characteristic traits of historical cities until serial sprawling cities put an end to the creative momentum of most cities and destroyed the continuity of their morphology.
8. The dynamics of historical cities made forms and activities converge, while modernism and urban sprawl separated the two.
9. The historical city increased its complexity and connectivity as it grew, whereas the morphology of the modernist city was simplified and its connectivity was reduced by a factor of twenty when measured with the help of graph theory.

The evolving nature of cities is linked not only to forms and functions but also to a key third element: connectivity.

An analysis of resilience has to be based on the forms, functions and connections. The connections are no doubt the most fundamental element for creating a living and sustainable city. Some periods are dominated by the creation of new forms, functions or connections while others are characterized by the persistence of existing patterns (Tannier, 2009). We have witnessed over the last thirty years the destruction of historical urban forms or their dilution in vast formless agglomerations, along with the destruction of connections (divided by two in the historical center of Boston), the erasure of forms and the segregation of functions. The accelerated urbanization of the planet is paradoxically a huge anti-urban production.

2.4 THE PERMANENCE OF THE PLAN

The study of city plans affords valuable indications as to their type and level of connectivity. Notwithstanding differences between periods and civilizations, historical cities display relative unity insofar as connectivity is concerned – a unity with which modernism made a radical break. We can analyze the resilience of an urban form by looking at the role of the street. The city is born in a precise place but it is the street that gives it life. "The association of the destiny of the city with communication arteries becomes a fundamental principle of development." (Rossi, 1981)

The urban land is at once a fact of nature and a product of civilization. It is linked to the urban composition where each element must be the most faithful expression of the life of this collective organism, which is the city. According to Aldo Rossi, "at the basis of this organism that is the city is the persistence of the plan." (Rossi, 1981) The concepts of persistence and of memory are essential to the resilience of cities. Rapid, brutal transformations of urban fabrics destroy the continuity and resilience of cities. Persistence is in fact the generator of the plan. The urban structure is a material structure formed of streets, monuments, and so on, but it is also a structure that internalizes continually changing social forces along with the forces of nature, subject to the unpredictability of deterministic chaos. Amid transformations, and sometimes amid catastrophic breaks, what persists is the urban fact. What constitutes an urban fact par excellence is the capacity to subsist within a totality in transformation. The functions, single or plural, that the city fulfils over time are only temporary moments in the reality of its structure. Resilient living cities maintain their axes of development; they preserve the placement of their arteries; they grow while continuing to conform to an orientation and a sense determined by older facts whose memory has often been erased.

To survive a city has to be able to evolve in a continuous metamorphosis and adapt to new needs, which necessarily implies deformations to its initial plan. The evolution of cities shows that successful urban developments are based on an interaction between urban planning and processes of self-organization that make the overly regular aspects of the initial organization more complex. In addition, the original form of the founded city must be able to deform successfully. The capacity of urban structures to last over time depends on the complexity of their organization, the intricacy of their network, the richness of their connectivity, and the creation of a fractal order of the same level of complexity on several very distinct scales. A city can be said to be resilient if the idea of its form is maintained through successive metamorphoses but not fixed for all eternity in an unchanging order. Cities like Turin, Florence or Rome survived the centuries and different civilizations. With each metamorphosis enough of their different successive forms was maintained to keep their memory alive while leaving their future open.

3 THE RESILIENCE OF FRACTAL URBAN FORMS

3.1 THE STABILITY OF FRACTAL URBAN SYSTEMS – EMERGING PROPERTIES

The fundamental notion that defines the stability of physical systems is that states are only stable if minor perturbations reinforce rather than destroy them. Dynamically stable urban states are those that display an enormous number of geometric and functional connections on different scales. When some connections are cut, others are created. These connective forces act on urban morphology to generate unique cities every time and transform them following singular trajectories. The process is exactly the opposite of the utopian or imaginary orders that architects try to impose on cities and that offer few connections. Huge quantities of energy are needed in such imaginary orders to maintain the urban system in a stable state. Modernist cities, with forms imposed from the outside, obstruct the emergence of connections whereas the continuous creation of connections in historical cities favored their evolution and hence their survival. Traditional buildings, because of their connective forces, have a stabilizing impact on the urban fabric and system. Modernist buildings do not connect into the urban fabric. They have a destabilizing impact and fail to create a human environment. Indeed modernist architects tried to reverse the laws of urban growth by working with large-scale elements. The brutal juxtaposition of vast homogeneous zones made of a repetition of very big objects hinders the appearance of emerging properties.

Emerging properties are properties that were not integrated into the initial conception of the system. For a property to emerge on a big scale, small scales need to exist to support it. Each scale supports the higher scales in the hierarchy. The fact that a system has emergent properties is what allows it to repair and stabilize itself and to evolve. We cannot understand emergent properties by breaking down the system and analyzing its parts. Emergent properties are analogous to the human brain (Edelman & Tononi, 2000). The three conditions needed for emergence to appear in a system are: a high connectivity, the presence of a mechanism that creates new connections and a sufficiently low degree of control, since less control implies more emergence and vice versa.

3.3 COMPLEXITY, COHERENCE AND URBAN RESILIENCE

A fundamental attribute shared by resilient living cities is a high degree of organized complexity. The geometric assemblage of elements constitutes a series of organized wholes on each successive scale and across the progression of scales. This fractal harmony is what distinguishes a coherent urban morphology from the repetitive serial din of modernist non-compositions. Urban morphology is fractal by nature. Modernist cities, on the other hand, are incapable of generating urban coherence. Geometric coherence is an indispensable quality insofar as it connects the city through forms across all scales. It is crucial to the vitality of the urban fabric.

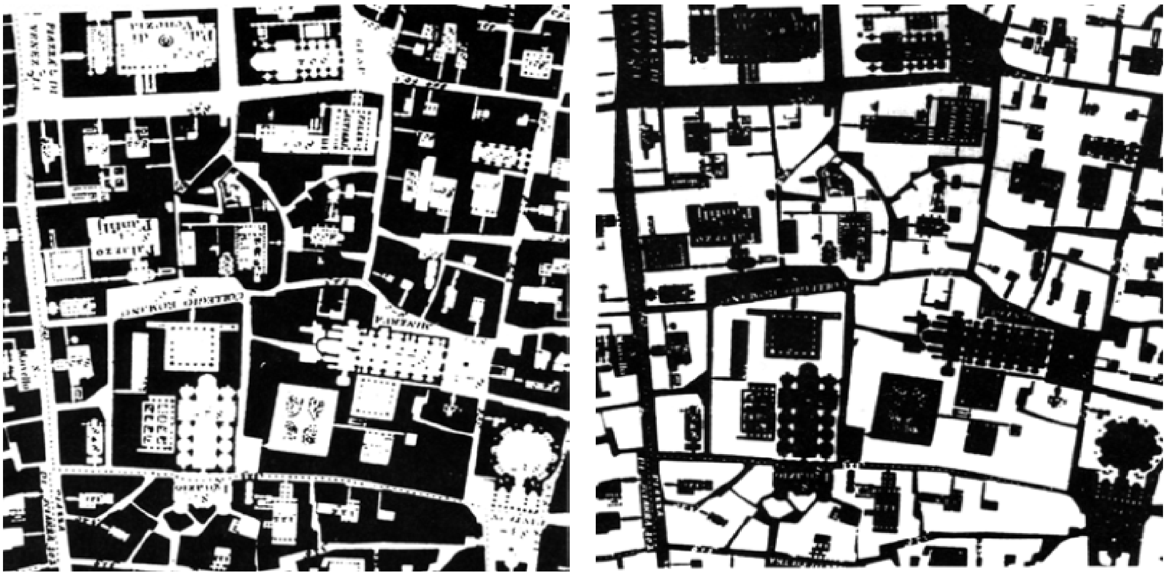

Fig. 2 The map of Roma drawn by Giambattista Nolli in 1748 (details)

In a fractal morphological field like the one we have just described the position and even the form of each element are influenced by its interaction on different scales with all other elements. When the result of all these interactions creates a form, it is neither symmetrical nor fixed. It displays a degree of plasticity that allows it to evolve. Evolution is only possible if the large scale is correctly defined on the basis of a great many connections obeying a hierarchy of scale.

The structure of the connections is what matters and not the nature of the components. In a multiply connected, living organic structure, the smaller components can be changed without affecting the overall structure. Building the whole from the parts in an organic way leaves room for evolution. Arriving at the parts, on the other hand, in a rigid way starting from the whole creates structures that cannot evolve. In concrete terms, modifying the whole once it has been established involves destroying a great many components on very different scales. It is, to the contrary, very easy to modify smaller components, like the arrangement of rooms in a house or the nature of buildings along a street. The streets themselves participate in the structure of the whole and display remarkable permanence over time.

According to Nikos Salingaros (Salingaros, 1998), the idea underlying the resilience of fractal street patterns is very simple: a complex city is a network of paths that are topologically deformable. This is particularly evident in Tokyo and Kyoto where, despite differences in form – in one case very regular, in the other, curved, labyrinthine and deformed by the topography – the topological structure of the graph of the two cities is identical and translates a fundamental anthropological dimension of Japanese society. In the same way, to be resilient, the urban form must be deformable and display a high degree of plasticity. It must be capable of accompanying the torsion, extensions and compressions of paths without tearing. To be deformable, the urban fabric must be strongly connected into the smaller scales and weakly connected into the large scale. This is also a characteristic of the Japanese city with its multiplicity of short-range connections and average distances between intersections of around 50 meters in Tokyo as in Kyoto. Connectivity on all scales following the inverse power law produces urban coherence. Tokyo and Kyoto are thus particularly coherent cities because they display a great number of small connections.

3.4 RESILIENCE AND MULTIPLE CONNECTIVITY

The multiplicity of connections enhances the resilience of a city and its possibilities of evolution, change and adaptation. In fact, the more connections there are, the more likely they are to be redundant. Thus, if the connections are cut, as they were for example during the successive fires in Kyoto, the city can continue to exist even as it changes. Districts can be reborn from their ashes, sometimes after centuries. They persist simultaneously the same and different, like Rome's Forma Urbis that continued to exist in Renaissance Rome and has survived in contemporary Rome.

Salingaros demonstrates that complex cities are those whose network displays a large degree of redundancy. If there are a great number of ways of getting from one point of the city to another passing through different nodes, then cutting a connection between two nodes will not keep the network from working.

Multiple connectivity also presents many functional advantages. Too many connections of the same type in a single channel can overload the channel's capacity. We can see this in overly hierarchical systems with the problem of collectors that gather the traffic from lower-level paths. On the other hand, connections of a wide variety of types create a less hierarchical network but one that is connected in a much more diversified way and this prevents the saturation of a single channel or gridlock caused by congestion at an unavoidable node. The different networks, on different scales, need not coincide. If they do, network saturation will take place faster. A good example of a resilient network is the Tokyo metro, which consists in multiple superimposed and intertwined networks.

4 SCALE HIERARCHY AND STRUCTURAL OPTIMIZATION

How are we to approach new urban projects in ways that embeds cities in the long term, and factors in the constraints we are facing in a finite world and the risks of climate change? Cities will have to reinforce their efficiency and resilience to meet these changes. They will have to be more efficient in their use of material and energy resources to reduce their ecological footprint and their climate impact. They will also have to rediscover the resilience of historical cities, in order to withstand climatic and natural shocks, and to absorb fluctuations in their environment, which will increase in number and intensity as the Earth's atmosphere warms.

We will show that for an urban fabric to be efficient and resilient, it must be structured in a complex way, strongly connected in the manner of a leaf, and hierarchized in a fractal way according to the Pareto scale-free distribution.

4.1 SIMON'S WATCHMAKERS' PARABLE

In a seminal paper, Herbert A. Simon (1962) introduced the topic of complexity architecture with a parable that has since largely influenced complexity sciences. He told the story of two highly regarded watchmakers, who constantly had to pick up the phone to answer clients. One of the two fine watch businesses, run by Hora, prospered, while the other, run by Tempus went bankrupt.

The two watchmakers had to construct watches out of 1000 parts each. Tempus' watch was designed so that if he had partly assembled it and had to put it down to answer the phone, it immediately fell to pieces. The more clients he had, the more they phoned him, the more difficult it became to have enough time to finish a watch. On the contrary, Hora's watch were designed so that he could put together subassemblies of about ten elements each, then put together ten of those subassemblies into a larger subassembly, and so on. Whereas a phone call caused Tempus' work to fall entirely into pieces, it only causes Hora a subassembly to fall into pieces. No need to argue further that the probability for Hora to finish a watch is much higher than for Tempus.

This parable was meant by Herbert A. Simon to highlight the role of hierarchy within complex systems: a complex system made up of coherent subassemblies has a greater ability to evolve and adapt quickly. And as we will see later in this paper, adaptability has crucial implications on resilience ability.

4.2 SCALE HIERARCHY, FLUCTUATIONS, AND RESILIENCE

Historical cities, over the course of their long history, were slowly transformed by incremental phenomena of destruction and reconstruction of the urban fabric. Structures that were not resilient enough were eliminated. And so historical cities have come down to us with extraordinary capacities of efficiency and resilience. In a process of ongoing, spontaneous self-organization to adapt their forms to fluctuations in their environment, historical cities acquired the capacity to absorb fluctuations by reinforcing their structure and order, and becoming more complex and richer as a result of the changes that take place in them.

Fig. 3 A free scale network (left) and the Parisian street network (right)

Scale hierarchic structures optimize urban flows and are also vital in giving cities the resilience that they are lacking today. The more structured and complex the city, the more readily it can be nurtured by the perturbations to which it is subjected, absorbing them without letting them upset the stability of its structure. And it is in assimilating the fluctuations and tensions that it complexifies and absorbs them all the more easily. Hence, there is an ongoing dialogue between the city's capacities of resilience and the constraints to which it is subjected, between the fluctuations from the outside environment and its resistance to these fluctuations.

The resilience of a city is intrinsically linked to its self-organizing capacities. But self-organization is inevitably lodged in time, and the long span of natural fluctuations is not that of contemporary cities; the latter are designed and built very rapidly by authoritarian, rigid forms of urban planning to accommodate an ever growing number of rural migrants irresistibly attracted to cities. These cities are designed nearly instantaneously in emerging countries, without the time and distance needed to evaluate the quality of their interactions with the environment, the adaptation of their forms to the flows that run through them, and the systemic efficiency that determines their resilience. These are cities that are expected to survive for centuries but the long span of their existence is almost never taken into consideration when they are designed.

Alongside these long fluctuations, whose effects over centuries are sometimes imperceptible, there are short-term, even catastrophic fluctuations, which are becoming more frequent today, with their share of deaths and destructions. Cities were always subjected to them. Cases in point are the Great Fire of London in 1666 and the earthquake in Lisbon that outraged Voltaire so. But London and Lisbon both managed to live through these disasters and maintain their form, whereas contemporary cities are more and more vulnerable to earthquakes, droughts, floods, and natural and energy crises. They are vulnerable, to begin with, due to their low efficiency, and their voracity in energy and resources. They are also vulnerable because they are not adapted to their sites, to the environment they inhabit all in the same way and which, from one day to the next, may violently remind them of its existence and its identity, like the Chao Phraya delta into which Bangkok is inexorably sinking. Finally, they are vulnerable because of the disordered uniformity of their urban fabric, its absence of hierarchized structure, of identity based on the complexifications of a long history that forges a city's capacities of resilience.

Following Simon's parable (1962), the resilience of scale hierarchic structures is linked to their power to complexify so as to absorb fluctuations, to transform the currents of the waves of history and time into a constructive rather than a destructive force. Urban resilience can be understood as the robustness of urban structures and networks against random failures. Such failures might be small-scale failures (local transport network disruption, local energy supply disruption, etc.) or large-scale ones. According to Buhl et al. (2004, 2006), the resilience of a network – its robustness – can be evaluated by studying how fragmented the structure becomes as an increasing fraction of nodes is removed. The network fragmentation is usually measured by the fraction of nodes contained by the largest connected component (Buhl, et al., 2004). The move removal can be chosen either randomly or selectively. According to Albert et al. (2000) and Holme et al. (2002) real networks clearly deviate from the prediction made for random graphs. Moreover, several real networks have proved to be highly resilient to random node removal and highly vulnerable to selective node removal. Although they might not be the unique ones (Newman, 2002; Dunne, et al., 2002), scale-free networks do exhibit this specific feature (Albert, et al., 2000).

Counteracting the vulnerability of contemporary cities requires a real paradigm reversal, and a shift from a mono-scale conception to a scale hierarchic conception of cities. Only scale hierarchic structures in the case of flow networks can secure optimal efficiency and resilience, while limiting the propagation of local perturbations. But another parameter is just as fundamental for the capacities of resilience of cities, and that is the fine-grained connectivity of their subjacent structures. This parameter entails pushing our thinking beyond the tree-like structures prescribed by simple thermodynamic considerations.

4.3 ARBORESCENCES AND LEAF STRUCTURES

An arborescence is a highly hierarchic structure, and this hierarchization is precisely what causes its efficiency (Salat & Bourdic, 2011). This then is the first element we are seeking for the sustainable structure of the urban system: a strong scale hierarchy ensuring system efficiency. However, the connectivity of a tree is low: between two points there is only one possible path. And connectivity is an essential parameter of cities. For a city to be connected, it must be structured not like a tree but like a leaf.

A series of connections whose intensity obeys a Pareto distribution – scale hierarchic - increases resilience by preventing rapid and catastrophic fluctuations from spreading quickly through the system and disorganizing it. There should be few long-range connections and these connections should be weak to prevent the spread of disrupting fluctuations. Indeed, weak connections are what allow the fluctuations to be absorbed. On the other hand, a great many strong short-range connections ensure the system's deformability. If efficiency is linked to the arborescence of elements, resilience seems to be linked to a more abstract arborescence, that of the system of connections between elements the intensities of which should also obey a Pareto distribution.

As Alexander has noted (Alexander, 1965), one can readily see that street networks are not structured like trees: small streets are more often linked to one another or to several higher level streets, which is not the case in a tree structure. In fact, the underlying structure of these networks is what is called a "semilattice". A striking image of this type of structure is the system of veins on the leaves of most deciduous trees. Their leaves manifest a remarkable exception to the many tree-like systems observed elsewhere in nature. They display the same scale hierarchy, which proves again the universality of the Pareto distribution, but the midsize veins and the venules connect to one another, like the streets of a city, and so the connectivity is much stronger than in a tree-like structure.

4.4 THE MULTIPLE PATHS OF LIFE

The multiple connectivity and scale hierarchy that leaves and cities have in common enhance both their efficiency and their resilience.

Firstly, the loops that these structures contain, as Francis Corson has demonstrated, (Corson, 2010) manage variable flows more efficiently. The tree structure is most efficient when it comes to distributing stationary flows. But one of the characteristic features of urban flows is their extreme variability, both in time and in space. The semilattice structure absorbs these variations by distributing flows along different possible paths. This is impossible in a tree-like structure, where there is only one path between two points.

Secondly, the semilattice structure imparts greater resilience to a network. When a branch of a tree is cut, all those that grew from it will die too. In a leaf, if a vein is interrupted, the redundancy of the network will allow the flow to get around the interruption via secondary paths, so that it will only be partly slowed down by the degradation of the network. This is why cities structured like leaves are more resilient. Just imagine that a path is blocked by an accident: the flow is simply deviated onto other paths to irrigate the far side of the perturbation. A part of the leaf's network can be amputated and the leaf will go on living and converting light energy into nutrients. Thanks to the dilatation symmetry or the scale invariance linked to the Pareto distribution, nature has provided for redundancy on all scales to ensure the permanence of its structures. The simultaneous existence of small and big nervures having the same function contains a natural redundancy for living organisms that answers the objective of efficiency and resilience with an economy of volume.

5 CONCLUSIONS

We have discussed the theoretical underpinnings of what a sustainable and resilient city should be. This is a conceptual framework, governed by fractal geometry for spatial planning, the power law for distributions, and leaf structures for connections. The scale relationships between the different hierarchic levels of an arborescence, a leaf, and the blood and oxygen circulation systems in our bodies obey such a mathematical law. It states the frequency of an element's appearance and the span of a connection based on its hierarchic level: the smaller an element is, the more often it will be encountered in the system; the bigger an element is the rarer it will be. This fundamental law defines in itself the manner in which living organisms and things should be organized to optimize their access to energy, the use that they make of it, and their resilience.

City planning today has lost all its complexity and hierarchy of scale. It has become so simplistic, mechanical, and functional that its structural inefficiency causes an enormous waste of energy. It should possess the qualities that history has conferred upon cities: complex, connected, and structured according to scale hierarchies based on the Pareto distribution.

To reach these high levels of connectivity, complexity and scale hierarchy that make the efficiency and the resilience of historical urban fabrics, a set of innovative tools based on the science of complexity has to be settled. It is meant to be applied to the design of new cities, but also to the restructuring of hastily built cities, denatured by the ideas of modernism, mechanical bodies completely disconnected from the time of historical, organic cities.

REFERENCES

Albert, R., Jeong, H. & Barabási, A., 2000. Error and attack tolerance in complex networks. Nature 406, 378.

Alexander, C., 1965. A city is not a tree. Design, Volume 206, pp. 46-55.

Bejan, A. & Lorente, S., 2010. The constructal law of design and evolution in nature. Philosophical transactions of the Royal Society B, Volume 365, pp. 1335-1347.

Buhl, J. et al., 2006. Topological patterns in street networks of self-organized urban settlements. The European physical journal B 49, p. 513–522.

Buhl, J. et al., 2004. Efficiency and robustness in ant networks of galleries. The European physical journal B, 42, pp. 123-9.

Corson, F., 2010. Fluctuations and redundancy in optimal transport networks. Physical Review Letters, 29 January, Volume 104.

Dawkins, R., 1986. The blind watchmaker. s.l.: Longman Scientific and Technical.

Dunne, J., Williams, R. & Martinez, N., 2002. Food-web structure and network theory: The role of connectance and size. PNAS 99.

Edelman, G. & Tononi, G., 2000. A Universe of Consciousness. New York: basic books.

Heitor Reis, A., 2006. Constructal Theory: From Engineering to Physics, and How Flow Systems Develop Shape and Structure. Applied Mechanics Reviews, Volume 59, pp. 269-282.

Holme, P., Kim, B., Yoon, C. & Han, S., 2002. Attack vulnerability of complex networks. Phys Rev E Stat Nonlin Soft Matter Phys. 65.

Kay, J., 2002. On complexity theory, exergy and industrial ecology: some implications for construction ecology". Spon Press.

Latora, V. & Marchiori, M., 2003. Economic small-world behavior in weighted networks. The European Physical Journal B, 32, pp. 249-63.

Newman, M., 2002. Assortative mixing in networks. Phys. Rev. Lett. 89.

Newman, M., 2005. Power laws, Pareto distributions and Zipf's law. Contemporary Physics, May, 46(5), pp. 323-3351.

Rossi, A., 1981. L'architecture de la ville. Paris: L'équerre.

Salat, S., 2011. Cities and Forms, On Sustainable Urbanism. s.l.:Hermann.

Salat, S. & Bourdic, L., 2011. Scale Hierarchy, Exergy Maximisation and Urban Efficiency. ELCAS2, Nisyros.

Salingaros, N., 1998. The theory of urban web. Journal of Urban Design, 3, pp. 53-71.

Simon, H., 1962. The architecture of complexity. Proceedings of the American Philosophical Society, 106(6), pp. 467-82.

Tannier, C., 2009. Formes de cities optimales, formes de cities durables. Réflexions à partir de l'étude de la ville fractale. Espaces et Sociétés, 3(138), pp. 153-71.

Vance, J., 1990. The continuing city: Urban morphology in western civilization. s.l.:Baltimore & London.

Berdini, P. (2008), *La città in vendita*, Donzelli, Roma.

Brenner, N. (2009), "A Thousand Leaves: Notes on the Geography of Uneven Spatial Development", in Keil, R., Mahon, R. (eds.), *Leviathan Undone? Towards a Political Economy of Scale*, UBC Press, Vancouver.

Brunet, R. (1996), "L'Europa delle reti", *Memorie geografiche*, n. 2, Società di Studi Geografici, Firenze.

Castells, M. (1996), *The Rise of the Network Society, The Information Age: Economy, Society and Culture,* Vol. I, Blackwell, Oxford - Cambridge.

IMAGES SOURCES

First page: Portoghesi, P., *Natura e architettura*, Abitare la Terra, Ed. Kappa, Roma, 2005

Fig. 1: Nolli, B.G., Pianta di Roma, 1748

Figg. 2, 3: S. Salat, Cities and forms – on sustainable urbanism, Ed. Hermann, 2011

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