

Urban Complexity, Efficiency and Resilience

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1. Introduction

The relationships between urban forms and energy that are investigated in this chapter are an example of a more general idea: the relationships between structures and energy. This chapter aims at presenting structural laws that link urban-scale forms to their internal organization and to their energy consequences, expressing them in a simple and innovative way, and putting them in the broader context of complex systems energy. One of these complex systems is life itself. Beyond their mathematical form, the structural laws of urban energy deal with the relationship between forms and processes. If we want to create a sustainable society, then each aspect of what we do must follow living systems structural order. This structural order always results from a process. As Fritjof Capra explains in *The web of life* (1996), systems thinking requires thinking in terms of relationships and patterns.

Urban form and spatial structure constrain cities' functioning (individual spatial behaviours, land use) and cities' flows (travel, energy, water) and, retroactively, their functioning modifies both their morphology and their structure. The World Bank has recently pointed out the need for more systemic approaches, taking into account both forms and flows (World Bank, 2010). The Urban Morphology Lab works at dividing flows by a factor 2 to 4 – and thus at the same time urban footprint – just by optimizing urban forms.

What are the urban morphology parameters that influence and determine the energy flows going through cities? To answer this extraordinary difficult question, only a quantitative analysis, based on a theory of urban structures can bring clarification. There is an urgent need to address these issues. Cities are the main driver of climate change, the biggest energy consumers, and the biggest greenhouse gas emitters. Urban structures are complex artefacts that absorb energy and transform it into heat, according to thermodynamics laws.

When it comes to energy, one has to think in terms of making a more efficient use of depleting resources instead of thinking in terms of replacing energy sources one by the other. Any renewable energy cease being renewable if an intensive over-consumption is made of it. The share of renewable energy in the global figure of urban energy supply has to increase, but for renewable energy to be profitable, one should first increase energy productivity in cities. A city four times denser consumes four times less land and sixteen times less network infrastructure. And yet density variations between loose suburbs and historical cores are within a factor 16...

But this chapter does not only question the spatial aspects of urban energy. On the contrary, the approach encompasses a much broader scope. The temporal distribution of energy flows

is at least as important as their spatial distribution. The temporal match between supply and demand is for example critical to develop renewable energy. The distribution of energy quantities and energy qualities is another aspect that is worth being investigated. Exergy-based approaches that put a particular focus on energy quality and degradation provide very beneficial insights to optimize energy flows within the city. Authors' main objective in this chapter is to encompass in a comprehensive way the structural parameters that make a city be sustainable.

At the crossing between thermodynamics, industrial ecology and urban morphology, this chapter summarises the lessons that can be drawn from several scientific fields and applied to urban analysis. Section 2 aims at defining what urban structure is and introduces the fundamental concept of urban complexity that is unfortunately rarely if never used - perhaps because it is hard to handle. Authors particularly focus on the hierarchy of scales within urban systems. Section 3 aims at highlighting the impact of urban structure and complexity on cities' structural efficiency and resilience. This dual approach rests upon some major scientific breakthrough of the last decades, such as fractal theory or complex systems thermodynamics. The approach though aims at a pragmatic objective, keeping in mind that urban development is in the end primarily decided by policy-makers and urban authorities. That is why authors eventually provide some examples showing the concrete and practical implications that these results have on the real urban world: bioclimatic comfort and passive urban structures, efficiency and resilience of urban transport networks.

2. About cities, urban structures and complexity

2.1 What makes a city a city?

There seems to be a great variety and complexity of cities around us. Yet approaching them with a scientific spirit means looking for what is simple behind this seeming complication. Paris and Tokyo, unlike Vienna, Barcelona or Kyoto, grew without a real general plan. But their material structure, as impermeable as it may be to all forms of topographic regularity, nonetheless evinces a very complex form of order, different for two cities, marking them with the seal of an irreducible identity. Paris remains firstly "a gigantic mosaic", closer to the structure of Pergamon than to those of Le Corbusier "Contemporary City for Three Million Inhabitants". "A sort of bit territorial weave", writes Bruno Fortier, "in which passageways established on the land of former convents, quarries turned into gardens, pagodas introduced into the civil fabric, remains of the World Map, connecting between them a few of its monuments were found intact, playing a remote score that no project really brought together." (Fortier, 1989, p. 15)

Yet what emerges from plans of Paris, as of Tokyo, is never incoherent: on different scales, the plans never cease to reveal stable structures, different for the two cities, where the course of streets as deformed as it may be by the topography or simply by history, evidences constants. The dense heart of Paris, like those of Hong Kong or Melbourne, that were conceived by Europeans, present a grid with an average distance of 120 meters between intersections, when it 50 m is more finely articulated urban settings such as Tokyo and Kyoto. In both cases, the pattern is immediately picked up, on the interior this time, by a remarkably dense interior. In every period, these cities chose in different manners, adapted to their culture, to have recourse to a limited number of schemes whose presence structure their cityscape.

If we turn our attention to these cities without preconceived plans but which, beneath the extreme variability of accidental forms, evidence astonishingly stable subjacent topological and metric structures, along with “signatures” each time that identify their natures, we can attempt to explore two questions. The first consists in asking if the invention of the city, rather than investing in isolated projects, is not firstly a matter of “defining rules of assembly and coexistence of a living, constantly open range of elements” (Fortier, 1989, p. 16). Today, the complexity of these rules of assembly has been lost in formal impoverishment of modernism that has reduced the city to isolated objects. The ideal stock of objects in the historical city had its own coherence that organized its interplay of full and empty spaces, of breaks and continuities, of sequences and views. Modernism bequeathed to us de-structured anti-forms that fail to give coherence to the city, and stand in the way of its representation. But this view of the city, this hypothesis of a pragmatics of procreation based on a coherent grammar of forms by no means excludes the considerable variations of these grammars over time and space. This then is a second level of study that opens up and that will be developed here, that of understanding the minimal threshold of complexity and of articulation that makes for rule of organization of these urban wholes that constitute an intelligible language and not a disorder of confused sounds, that produce a human environment and not a bursting where a non-qualified void distends the discordant notes of an urban harmony that seems forever lost. It is ultimately in search of these minimal rules of organization of urban areas that we must go, not to copy the past but to move toward morphologies that are at once vaster and more intimate, integrating scales never before seen, of human concentrations of tens of millions of inhabitants, in urban areas that nonetheless succeed in giving everyone the reassuring intimacy of a comprehensible neighbouring space. These rules are those of complexity

2.2 Urban complexity

“What is complexity? At first glance, complexity is a fabric (*complexus*: that which is woven together) of heterogeneous constituents that are inseparably associated: complexity poses the paradox of the one and the many. Next, complexity is in fact the fabric of events, actions, interactions, retroactions, determinations, and chance that constitute our phenomenal world.” (Morin, 1990, p. 21). Two illusions, discussed by Edgar Morin, are to be avoided. The first would be to think that the complexity is such that it is impossible to draw out urban facts, clarity and distinct knowledge from the confusing and sometimes nebulous cluster.¹ The second would be to conflate complexity and completeness. We know from the start that a complete knowledge of the city is impossible: one of the axioms of complexity is the impossibility, even in theory, of omniscience.

However, the aim of a complex approach to the city is to bring together different forms of knowledge whose connections have been broken by disjunctive thinking. We are looking for a multidimensional analysis integrated by overarching universal laws that govern cities as well as the size and the distribution of clusters of galaxies, the evolutionary tree for species or the frequency and amplitude of economic cycles (Nottale et al., 2000). Complex thinking strives to establish the greatest possible number of connections between entities that must be

¹ Le Corbusier thought, by simplifying and classifying, atomizes the city into independent elements like those of a machine. Complex thought on the contrary refuses the mutilating and unidimensional conception of modernist simplification.

distinguished from one another but not isolates. In this it has the same structure as the cities that Nikos Salingaros (2006) showed to be living only if they establish a very great number of connections. In the realm of thought, Edgar Morin observed that Pascal had posited precisely that “all things being caused and causing, assisted and assisting, mediate and immediate, and all of them joined by an intangible natural bond that connects the most distant and the most variant.” (Morin, 1990)

This general bond between all things brings us to pose the problem of the relationship of the whole and the parts and the links that they establish on different scales. Recent morphological theories conceive of forms not only as autonomous entities but also and especially *globally* as totalities irreducible to the sum of their parts. This is a point that Salingaros stresses: complex systems ordered by a hierarchy of coupling forces of short and long range, cannot be broken down into parts (Salingaros, 2006). This is also a point on which Ilya Prigogine insists. “One of the most interesting aspects of dissipative structures is their coherence. The system behaves as a whole, as if it were the site of long-range forces.” (Prigogine & Stenger, 1984, p. 171)

Urban complexity can be understood as successive urban scales, revealing hierarchical levels of organization within a city. In these hierarchies, some sets of consecutive levels display a much better determined arrangement than others, which are much looser. The description of a “well structured” set generally introduces the notion of structure: the higher level element is broken down into lower order elements according to a well-defined scheme that can often be predicted to a great extent beforehand. The hierarchical order linking the frequency of appearance of elements to their size is, as we will see, a fractal order (see section 3.1). Generally speaking, fractal theory is a theory concerning the broken, the fractured, the scattered or yet about the granular, the porous, the tangled. But the strength of the theory is to have identified an order beneath the disorderly appearance of these irregular forms: the complex order of objects folded in multiple ways.

Urban limits, and the size and distribution of land uses and networks obey fractal laws (Frankhauser, 1994). The notion of fractal structure accounts for the economic localization of urban activities. On a still higher scale, it makes it possible to synthesize the analysis of urban density with the notion of the hierarchy of central places. Urban geography and in particular the theory of central places underscore the fact that cities exist not in isolation but rather as part of hierarchic systems that Batty and Longley (1994) demonstrate obey in rank and size a fractal distribution.

The hierarchy between urban scales, from the neighbourhood to the city, from the brick to the building, is a fundamental aspect of urban complexity.

3. Complexity, efficiency and resilience

Urban world is experiencing a never before seen growth. When put into perspective with climate change issues, fossil energy scarcity and poverty issues, this growth highlights the crucial need for more sustainable cities, be it on the energy or socio-economic side. Concerning climate change, two concepts play the major role: mitigation and adaptation to climate change. Mitigation aims at decreasing the amount of greenhouse gas emitted in the atmosphere to reduce the effects of climate change. On the other hand, adaptation is an anticipated approach to prepare to the inevitable effects of climate change.

The Urban Morphology Lab investigates these two concepts, putting them into perspective with two related ones: urban efficiency and urban resilience. Cities' efficiency is closely related to climate change mitigation. Considering cities, how can one get better services and more well-being with less resource consumption and less negative impacts? Urban resilience is related to climate change adaptation: what is the ability of a given city to resist to a series of endogenous and exogenous stresses (increase in resource prices, socio-economic instability, rise in temperature, and rise in sea level...)? Both will be crucial in the century to come in the climate change and resource scarcity compelling context.

3.1 Efficient cities

Various prisms allow investigating cities' structural energy requirements. Thermodynamics is one of them. However, using thermodynamics to assess cities energy efficiency appears to be everything but easy. Classical thermodynamics, that is widely based on the second law of thermodynamics (entropy maximization principles), fails to properly assess cities (Salat & Bourdic, 2011). Classical thermodynamics is fundamentally based on reductionist assumptions: any system can be analyzed as the sum of its elements. As authors have been explaining throughout this chapter, this reductionist approach is nothing but adequate for cities. Another reason for this failure is that classical thermodynamics has been developed to analyze closed systems. But cities are mainly driven by external flows: energy flows, material flows, information flows, etc. Cities are not closed systems. Cities exist because of their openness. As such, applying classical thermodynamics to cities is a nonsense. Fortunately, recent developments in thermodynamics provide interesting insights for open flow-driven systems such as cities.

Building on these recent developments, the Urban Morphology Lab bridges the gap between several fields of thermodynamics and shows essential results that have direct implications on urban energy efficiency issues. Salat and Bourdic (2011) base their demonstration on three main scientific areas:

- Prigogine's non-linear thermodynamics applied to open flow-driven systems (Prigogine, 1962, 1980)
- Kay's work on industrial ecology (Kay, 2002), analysing order emergence as a response from the system to make a more effective use of the available energy flows
- Bejan's "constructal theory", predicting the type of structure the most likely to emerge in a complex flow-driven system (Bejan & Lorente, 2010).

This chapter is not the place for digging into very theoretical aspects of thermodynamics and complex systems theory. That is why authors invite the reader interested in these fundamental aspects to refer to Salat and Bourdic (2011). To make a long story short, these three approaches are converging into a very same idea: open complex systems tend to be structured in the most energy-efficient way that is based on a power law distribution. In an open complex system, energy considerations impose a relationship between the different scales of the system. It imposes a mathematical relationship between the size of a given element and the number of elements of this size: few big elements, more medium-size elements, and a big number of small elements.

This power law distribution gives the number of elements (multiplicity) as a function of their size, as shown in Figure 1.

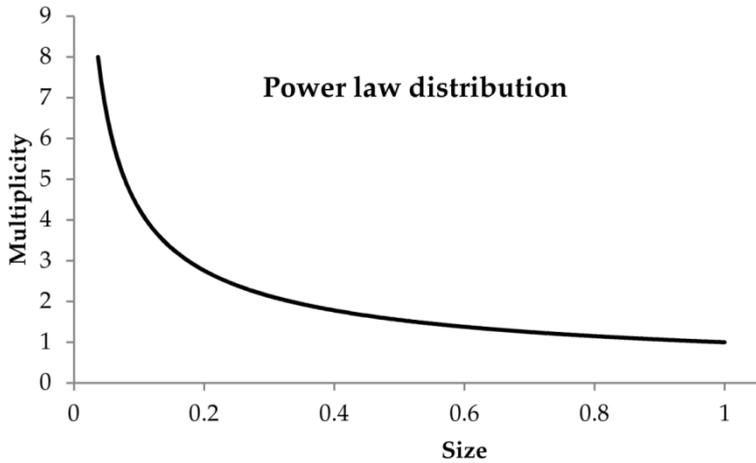


Fig. 1. Power law distribution, linking the multiplicity to the size of elements in a system.

The mathematical formula for such a power law distribution is given in Equation (1), where A is a constant and m the fractal dimension of the distribution².

$$\text{multiplicity} = \frac{A}{\text{size}^m} \quad (1)$$

Power laws have a tremendous importance in many natural phenomena. They allow describing a wide range of distributions with analogue properties: many small objects and few large objects, many small events, and few large events. This structural law is omnipresent in natural phenomena involving flows: lung and river basin structures, blood system, trees... But these types of distribution are also omnipresent in man-made phenomena - under the name of Pareto distributions -, be they social, economic or cultural: size of cities, wealth within a society, or even the number of visits to internet websites. Interestingly, these types of distributions, the one structuring natural flows, the other unconsciously structuring man-made organizations, are two sides of the same coin.

After a long time of evolution, after numerous processes of construction and destruction, a whole series of systems have become more and more efficient over time, by moving toward more efficient structures. This motion has been an increase in structural complexity. To become efficient, systems have complexified at each and every scale, from the biggest elements to the smallest ones. For this purpose, authors introduce the concept of scale free complexity which speaks for itself: concerning complexity, there is no predominant scale.

Making good use of these hard-core science theories, the Urban Morphology Lab applies them to cities. There is in fact no reason why this law that applies to all complex systems

² It is fundamental for the reader to notice that this relationship is non-linear. If there are X elements of size 100, the adequate multiplicity for the elements of size 50 is not simply $2X$. On the contrary, it is given by the equation (1). For a detailed analysis of this formula in urban context, see Salat (2011).

should not be used to improve urban efficiency. This fundamental law can indeed help make urban systems structurally more efficient, by respecting the right hierarchy of scales in urban systems: some big elements, a medium number of medium-size elements, and a very big number of small elements. As it will be shown later on in this chapter, this framework is a generic one, that applies to a wide range of parameters: transport networks, size of courtyards and buildings, socio-economic structure... To easily handle this structural law, the Urban Morphology Lab has created an innovative tool-box aiming at assessing the structural efficiency of urban structures (see section 4).

3.2 Resilient cities

Another interesting insight from the theory of complex systems deals with resilience. Understood as the ability to overcome endogenous or exogenous stresses, crisis and shocks, cities' resilience is an issue that is worth being investigated in current context. Cities will be confronted to a whole series of stresses throughout the century to come: water stress, increase in urban population, socio-economic crisis, natural resources scarcity, climate change, etc. This section aims at presenting the influence of urban structures on cities' resilience.

For this purpose, let us briefly open a parenthesis to introduce and explain the difference between a tree and a leaf. Mathematically speaking, a tree and a leaf have extremely different structures. Let us consider a small branch in a tree. It belongs to one, and only one bigger branch (see Figure 2). If you cut the bigger branch, the small branch falls and dies. The leaf structure on the contrary gives rise to a much bigger complexity. A small vein does not only "belong" to one bigger vein in the leaf, but to several (see Figure 3). A leaf is entirely structured by interconnected loops at every scale: there is a scale-free feedback looping. This point constitutes the fundamental difference between leaves and trees. If you cut a vein in leaf, the sap flow will be entirely compensated through the upper and lower levels of veins: the leaf survives.



Fig. 2. A tree structure (Portoghesi, 1999).

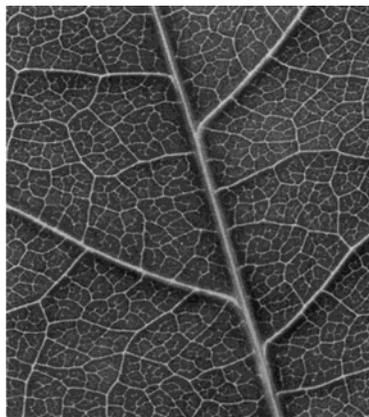


Fig. 3. A leaf structure (Portoghesi, 1999).

Surprisingly, this point has direct implications on cities and urban networks. Since Edison, electricity and energy networks have classically been structured like trees: a big remote power plant unit pouring the electricity flow into overhead high voltage power transmission lines, eventually reaching the consumer after having been cascaded into a series of lower voltage power lines. Tree-like structures are not resilient: cutting a branch in the tree leads to the loss of all the small branches belonging to this branch. Damage in the big remote power plant or in the high voltage line impacts a whole part of the network. On the contrary, leaf-like structures are resilient: damage in a vein of the leaf is immediately compensated by flows in parallel circuits, causing less if not no damage in the rest of the leaf. Analyzing leaves and trees' structures, Corson (2010) shows that redundancy³ within leaves' venations improves the tolerance to damages.

This result has direct implication on transport networks (Dodds, 2010; Katifori et al., 2010) and can also be transposed to all sorts of urban networks: electricity, energy, water, waste, etc. The tolerance to damages and shocks can be interpreted as the adaptation and resilience ability of urban systems. Multi-scale interconnected loops, redundancy and connectivity could thus lead to an improvement of the resilience and adaptability of urban networks. In the climate change and resource scarcity context, instabilities and shocks will become more and more frequent, and adaptability and resilience become all the more crucial. Theoretically speaking, creating interconnected loops at every scale of urban networks correspond to a move toward a leaf-like structure at the urban scale, and therefore a move toward more adaptive and resilient structures.

Urban tissues resilience is an indicator for cities' stability and has therefore a strong influence on long term economic value. Resilience of urban systems is heavily dependent on its level of redundancy. In a highly dense and connected city with high levels of complexity, functional mix allows sparing significant amounts of inputs (materials, energy...). Furthermore, high levels of complexity and density make it easier to manage residual needs in a circular economy structured by feedback loops at every scale.

³ Redundancy stands for the multiplication of elements or functions of a system to improve its stability and its reliability. Since each element rarely fails, and is supposed to fail independently from the others, the probability of all redundant elements failing is extremely small.

4. Concrete implications for the urban world

The investigations presented earlier in this chapter may appear dry and theoretical to the reader. However, they have very sound, concrete and direct implications on cities.

4.1 Bioclimatic comfort, heating and cooling energy efficiency

Heating and cooling requirements represent a very significant part of urban energy consumption, respectively in cold and hot climates. The current trend is to foster energy efficiency of systems (heating and cooling systems) and buildings (insulation and glazing). The approach of the Urban Morphology Lab rests on a wider understanding of urban efficiency. This approach, inspired from von Weiszäcker et al. (1997), is based on 4 leverages to improve urban efficiency, as shown in Figure 4.

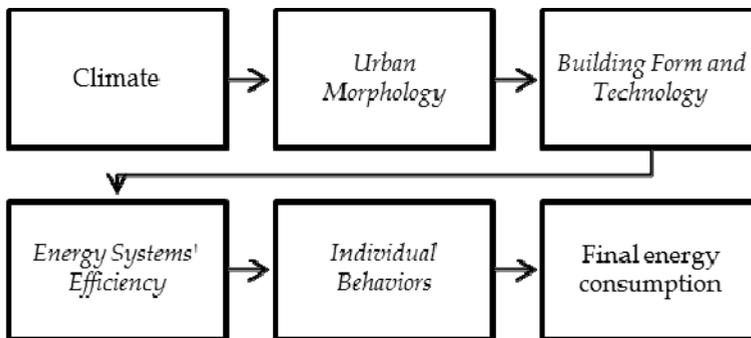


Fig. 4. Four leverages to improve urban energy efficiency (displayed in italics).

Whereas most of the current efforts aim at improving buildings' technology and energy systems' efficiency, very significant reductions in final energy consumption can be achieved by tackling the two other leverages that are urban morphology and individual behaviours. The Urban Morphology Lab mainly focuses on the first leverage that is responsible for a factor 2 to 2.5 in the final energy consumption. In other words, everything else being equal, a city with an appropriate urban morphology has a structural energy consumption that is 50 to 60% smaller than another city with a "bad" urban morphology. This section shows how complex urban structures can be structurally more efficient than simple ones.

Taken as a whole, a city is nothing else but a membrane exchanging a wide range of flows with the outside: air, heat, solar radiations, etc... The following analysis aims at showing how fractal theory can help optimize the interface between the building and the outside, with the example of passive zones. The concept of passive zone is described in the LT-method (Baker & Steemers, 1996) as being the area in the building within a distance from a perimeter wall, usually between 6 and 8 meters, depending on the floor to ceiling height (see Figure 5). These passive zones benefit from natural lighting and natural ventilation, but also from useful solar gains in winter. The energy consumption associated with lighting and ventilation is thus expected to be lower in these zones, an important part of lighting and ventilation being 'free'. On the contrary, these zones suffer from heat loss through the envelope and from unwanted solar gains in summer.

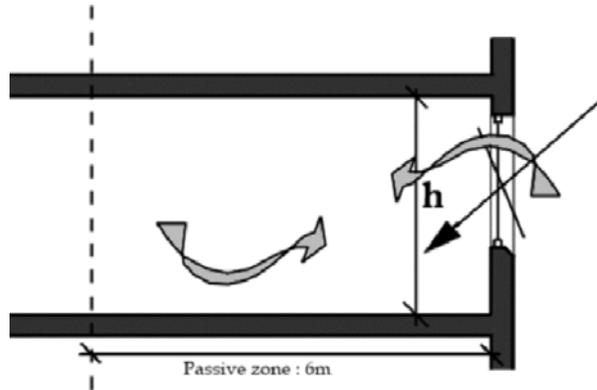


Fig. 5. The passive zone is located less than 6 meters from the façade (Ratti et al., 2005).

But as building technologies improve significantly at the present time, notably concerning glazing and insulation, the share of this unwanted phenomenon in the overall energy consumption figure will tend to diminish significantly in the future. In the office buildings, energy consumption is mostly associated with lighting, ventilating and cooling, even though the outside temperature is low. Concerning residential buildings, improved glazing and insulation will diminish the share of heating in the overall energy consumption figure in a close future. As it is already the case in office buildings, the share of ventilation, lighting and cooling will increase.

Strategically speaking, the role of passive zones will become more and more significant in the coming years and decades, as the benefits from improvements of insulation and glazing will become marginal. The more passive zones in the building, the better. Unfortunately, it is much harder to improve the passive volume ratio⁴ of a building than its insulation. This ratio entirely depends on the original form of the building. If the passive volume ratio of a building is low, it is almost impossible to change it, but to destroy and rebuilt. Whereas improving insulation or glazing is a matter of months or years, improving passive volume ratios is a matter of several decades, *i.e.* the lifespan of the building.

The approach defended by the Urban Morphology Lab though rests upon an ability to scale up urban issues. Passive volume ratios are a characteristic on the building scale. But considering this issue from the neighbourhood or the district scale provides interesting insights. The following analysis is based on the neighbourhood scale. It aims at showing how passive volume ratio may increase as urban fabric becomes more complex. In the six situations, the zone under consideration is a 200x200m square, in which the building occupies 70% of the available floor area. The first three examples display simple urban organizations on which most of modernist cities have been based.

Figure 6 displays a mono-block structure, typically a tower. Passive zones are in green whereas non-passive zones are in black. The passive volume ratio (PVR) is only 17%, which is extremely low and leads to high energy consumptions notably for lighting, ventilation

⁴ The passive volume ratio corresponds to the ratio of the volume of passive zones within a building over the total volume of the building.

and cooling (even in cold climates). The reader will certainly notice that unfortunately most of the office buildings – where energy consumption is mainly associated with lighting, ventilation and cooling – are towers...

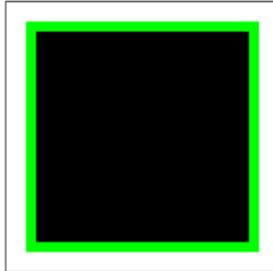


Fig. 6. One block, PVR=17%.

Figure 7 and Figure 8 display two other structures, with the exact same floor area ratio. The passive volume ratio remains below 60% in both cases.

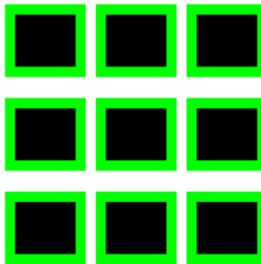


Fig. 7. 9 blocks, PVR=46%.



Fig. 8. Linear buildings, PVR= 58%.

Figure 9, Figure 10 and Figure 11 show three structures based on square courtyards, with a growing complexity. The construction is directly inspired from fractal theory, and more precisely from a Sierpinski carpet⁵. Figure 9 displays a massive building with only one

⁵ For further information on fractal theories applied to urban structure, we invite the reader to refer to Batty and Longley (1994) and Salat (2011).

block, with one big courtyard: the passive volume ratio is low. In Figure 10, a second level of smaller courtyards has been added in the building. This leads to an almost doubling of the passive volume ratio. Finally, another level of courtyards is added in the building (Figure 11), leading to a passive volume ratio of 100%.

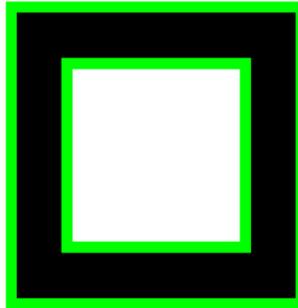


Fig. 9. One courtyard, PVR=33%.

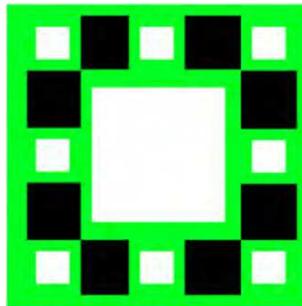


Fig. 10. Two levels of courtyards, PVR=60%.

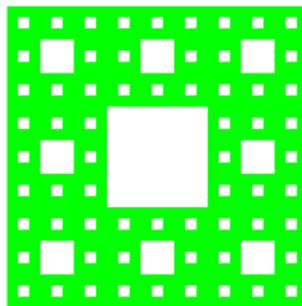


Fig. 11. Three levels of courtyards: , PVR=100%.

This simple geometric analysis shows that complex urban fabrics, based here on fractal theory, display a much higher passive volume ratio than simple ones. Fractal theory is a way to optimize the “urban membrane” – the interface between the inside and the outside. In Figure 11, the pattern is distributed over three scales, instead of one in Figure 9. The

careful reader will then certainly notice that the multiplicity-size distribution of courtyards in Figure 11 follows a power law. Further research is currently carried out to understand how size and scale hierarchy of courtyards impact on energy consumption patterns according to the different climates.

Pushing further this geometric analysis, authors have investigated numerous urban tissues, historical and modernist ones, in cold and hot climates. When analyzing real cities, the same kind of results emerge: the more complex the urban tissue, the higher the passive volume ratio. The four following figures display two modernist districts (800x800 m squares) and two historical ones. Passive zones are in dark grey, whereas non passive zones are in light grey. The two first districts are made of simple blocks, without any courtyard. In Shanghai Lujiazui Central Business District (Figure 12), elements are so massive that the passive volume ratio is smaller than 50%. In Tianhe district (Figure 13), there are two predominant scales of buildings. The small ones have an acceptable passive volume ratio, but the big ones have a dramatically low one, leading to an average passive volume ratio of 66%.

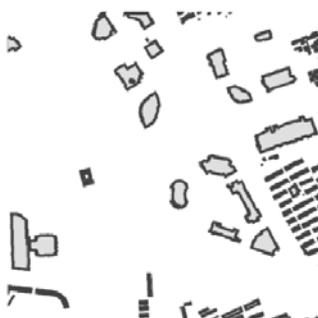


Fig. 12. Lujiazui (CBD), Shanghai. Passive Volume Ratio = 43%.



Fig. 13. Tianhe district, Guangzhou. Passive Volume Ratio = 66%.

In the two historical urban tissues, Shanghai's Lilongs on Figure 14 and a Parisian district on Figure 15, there are still some big elements. But they are organised around numerous courtyards of all scales that allow a much better interface with the outside, and a passive volume ratio higher than 80%. The analysis of the building size distribution and of the

courtyards size distribution shows that the two historical urban fabrics display a high scale hierarchy, close to an optimal power law distribution (see section 3.1).

Urban scale-free complexity is a way to optimise passive volumes in the urban fabric. Urban complexity is not about scattering numerous small elements, but on the contrary about respecting an adequate scale hierarchy: a small number of big buildings and courtyards, a medium number of medium size elements, and a big number of little elements. Modernist urban fabrics based on one scale (see Figure 12) are structurally speaking unsustainable. On the contrary, urban fabrics based on several scales (up to three or four fundamental scales in Figures 14 and 15) allow optimizing crucial parameters for sustainability, such as the passive volume ratio.



Fig. 14. Lilongs, Shanghai. Passive Volume Ratio > 80%.



Fig. 15. Paris district, 19th century. Passive Volume Ratio > 80%.

A proper urban complexity is a way to improve the passive volume ratio, and thus to optimize the interface between the city and the outside. Pushing the thought further, this approach aiming at optimize the urban envelope can have implications on the renewable energy potential of urban structures. An optimized and complex interface on the district and city scale is a way to increase, with the same land footprint, the available envelope area, and thus the available area for solar energy. Complexification of urban structures may thus also reveal to be a partial answer to the higher land footprint of renewable energy compared to fossil fuels.

4.2 Tools to assess urban networks' structural efficiency

The complexity analysis is transposable to other aspects of urban sustainability such as urban networks. Efficiency is crucial for designing urban transport networks. An efficient urban transport network aims at providing a service – make every location in the city easily accessible from any other location – with the least energy consumption. Based on the theoretical analysis presented in section 3, the Urban Morphology Laboratory has developed a tool-box to assess urban transport networks' structural efficiency, notably with a tool assessing the scale hierarchy of the network. This tool measures the distance (or deviation) between the network and the associated optimal one. A low value insures that no scale in the network is underrepresented: the highways, the large scale transport infrastructures, the medium streets and the bicycle and pedestrian networks are then in the right proportions. On the contrary, a high value shows that one scale of the network is either over or under represented in the network: the network is then structurally inefficient.

Equation (2) shows how to calculate this indicator for a system with N scales, each scale gathering n_i elements of size x_i :⁶

$$S = \frac{1}{N} \sum_{i=1}^N \left[1 - \frac{n_i x_i^m}{A} \right]^2 \tag{2}$$

For each scale i (i going from 1 to N) the relative distance between the number of elements of scale i and the optimal one is calculated. The indicator is then the sum of the squares of these relative distances. The closer this indicator to zero, the closer the actual network to the structurally optimal one. But if some scales are over-represented, under-represented or missing, the value of this indicator increases. The Urban Morphology Lab has analyzed two city-scale road networks to compare a historical city (Paris, see Figure 17) with the archetype of many urban cities (Contemporary City for 3 Million Inhabitants, Le Corbusier, see Figure 18).

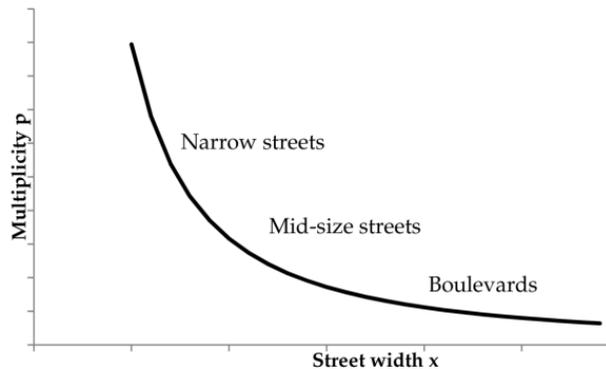


Fig. 16. Paris road size distribution.

⁶ For further details on the calculation of the constants A and m, we invite the reader to refer to Salat et al. (2010) and Salat (2011).

The Parisian network displays numerous scales of streets, and each scale is present in a proportion that is relatively close to the optimal one: there are some large boulevards, more mid-size streets, and a very big number of narrow streets (see Figure 16). The Parisian road network has evolved from a vernacular structure to a highly scale hierarchic one. Baron Haussmann, who designed Paris wide avenues in the late 19th century, gave Paris his current structure by superimposing a larger scale on the historical network. Far from destroying historical urban complexity, Baron Haussmann added one more scale to the Parisian network by cutting wide boulevards through the old urban fabric. Unconsciously increasing scale hierarchy, he gave a new coherence to the city, opening at the same time a new era for motorized transports (see Figure 17). The indicator presented here above highlights the good scale hierarchy of the network: it is equal to 0.17, which means the structure of the network is very close to the optimal power law distribution; The Parisian network respects a fundamental scale hierarchy, from the pedestrian pathways to the wide Haussmannian boulevards.



Fig. 17. Transformation of the street system, Paris, by Pierre Ladevan (Salat, 2011).

On the other hand, Le Corbusier designed in the early 20th century an abstract of what would become an archetype of modern cities: a regulated and geometric urban scheme, with little ground coverage but great height, and a mix of cruciform towers, setbacks, cellular units and extensive empty spaces (see Figure 18). Le Corbusier sought to decongest city centres, augment their density, increase means of circulation, and increase open spaces. Purism informs his architectural choices. The Athens charter adopted by the fourth International Congress of Modern Architecture in 1933 artificially separated four urban functions - living, recreation, working, and circulation - in opposition to the existing urbanism that was characterized by mixed-use and tightly interwoven functions. It is to this mixed-use model that sustainable urbanism today is seeking to return.

Le Corbusier explicitly proclaimed his desire to destroy the street. The Athens charter recommended replacing house-lined streets in the living areas with tall buildings set at some distance from each other to free ground space for big landscaped areas. The freed spaces were also meant to be utilized for playgrounds, promenades, and sports. In actual fact, when these modernist principles were applied, enormous motorways and parking lots occupied most of the freed ground space. People were driven off the streets of the city by

cars. Indeed, the need to speed up traffic was behind the idea of destroying existing urban fabrics, too cramped to meet the new needs of automobile traffic. The fact that functional zoning would lengthen distances between living and working areas and increase travel time was already noted in the charter. Instead of reconsidering functional zoning, its authors advocated the massive development of automobile transportation, replacing the many traditional streets of different sizes and the many crossroads with straight wide arteries.

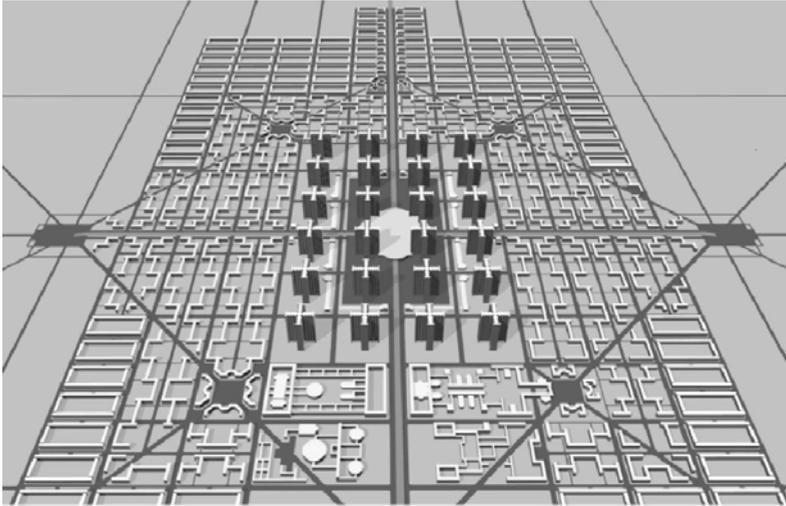


Fig. 18. Le Corbusier's Contemporary City for Three Million Inhabitants (Salat, 2011).

This destruction of the road network scale hierarchy is made obvious by the indicator assessing the distance between the network and the optimal power-law distributed network: it is equal to 509. It is 3000 times bigger than for the Parisian network. The Corbusean fabric is only made of three street scales: 240 km of 10 m wide streets, 220 km of 30 m wide streets, and 1,640 km of 50 m wide streets. All other scales are missing. The extremely high value of the deviation indicator shows that the scale hierarchy is reversed. Whereas the Parisian network distribution is very close to the theoretical optimum, Le Corbusier's is selective, discontinuous and reversed, allowing neither complexity nor coherence for the pedestrian, and offering no complexification potential over time.

Alongside with this major tool assessing networks' structural efficiency, the Urban Morphology Lab has used a wide range of complementary tools to assess both efficiency (proximity, scale hierarchy, ...) and resilience, with several tools that assess the level of connectivity (intersection intensity) and the redundancy (cyclomatic number, feedback loop intensity, etc...). Numerous urban tissues in Europe, Asia and America have been analyzed using these methods. Among other results, the analysis shows very significant differences between historical cities and "modernist" cities (see Salat, 2011). All the indicators show that most of the "modernist" cities eliminate essential scales in the network hierarchy, structurally banishing the low (or zero) energy transportation means (pedestrian and cycling) from the city. At the same time, the structural redundancy of urban networks tends to decrease, inducing a loss of resilience.

4.3 Economic insights

4.3.1 Path redundancy instead of element redundancy

Analyzing urban efficiency and urban resilience is not without raising a series of economic and financial issues. The first issue at hand concerns the concept of multi-scale redundancy that we showed earlier to be crucial for networks' resilience and stability. The role of redundancy is already well known and recognized as a key point for electricity networks. The main brake though on redundancy is of course the economic affordability. A twice redundant network induces twice higher costs.

Prima facie, this assumption seems to be true. But the approach developed in this chapter is a little bit more subtle. This approach requires going further than the reductionist paradigms and being able to grasp several scales at the same time. Authors have explained throughout this chapter the influence of complexity on efficiency and resilience, notably through the prism of scale hierarchic networks. Scale hierarchy does not induce higher costs. On the contrary, it allows sparing money. Let us take the example of a road network. If this road network displays only one scale (one street width) - as in many square grid based cities - the required amount of asphalt to achieve the same access to any location in the city is much higher than in a scale hierarchic grid - inspired from a lung for instance. The networks structured with only one fundamental scale are dysfunctional because most of the streets are either over or undersized.

Coming back to redundancy, let us just consider once again figures 2 and 3 that display a tree and a leaf structure. In a mono-scale network, increasing path redundancy means increasing the number of elements. But on the contrary, in a multi-scale and scale hierarchic network, a path redundancy does not increase the number of elements. It only curls the elements. Let us consider a tree structure. There is only one path to go from point A to point B. Now consider the same tree and curl the branches to connect the elements within each scale. The number of elements is the same, but the redundancy has extraordinarily increased. There are now dozens of paths to go from point A to point B. Increasing resilience in an urban network is thus not about an element redundancy, but a path redundancy instead. It is about connecting elements on all the scales instead of sprawling them apart.

4.3.2 The challenge of stability and resilience in the future

Stability and resilience will get a bigger and bigger importance in a close future. They have not been such a big deal so far, as most of the energy network depend on some big remote power plants, which energy production can roughly follow the demand. But the takeoff of renewable energy will induce a fundamental questioning of this paradigm. A crucial question of the next decades is how to increase the share of renewable sources in the energy portfolio. The main brake though on the renewable energy takeoff lies in their inherent instability and unpredictability. Over a 20% share of renewable energy in the portfolio, energy supply becomes fundamentally unstable. And this instability is expected to induce extremely high marginal costs, as very few consumers will accept random blackouts. The renewable energy takeoff is impossible and incompatible with the current energy supply (and demand) structure.

The current fashion around smart grids provides interesting insights on this issue. The concept of smart grids aims at making all the individual objects in the city (electric cars,

boilers, heaters, washing machines...) active participants of electricity supply, by making them communicate with each other. The implicit objective of these 'smart' approaches is to improve the overall resilience of urban systems. Smart grids are presented as the best solution so far, but remain *theory*. In fact, this concept relies on a series of assumptions that will be nothing but obvious in the coming years, notably a rapid and high market penetration of hybrid and electric vehicles. That is why there is an urgent need for solutions to improve the structural resilience and stability of energy networks in a close future. We hope the approaches we propose in this chapter will feed the thought.

5. Conclusions

Historical cities, from Sienna to San Gimignano, from Suzhou to Beijing, from Tunis to Jerusalem, are a vast laboratory for examining the relations between people, the climate and the urban environment. Faced the forces of nature – the soil, the sun, and the wind – these fractal cities were the outcome of generations of patient efforts. Conversely, the planners of the modernist city set out to raze real cities in the name of abstract principles and unreal theories about the primacy of right angles and simplicity, when all historical cities are multi-scale systems complexified by their irregular topography and hydrography, and by the curving paths marked out by human beings focalized on such centres of attraction as marketplaces or mosques. Whereas urban development used to be a movement towards complexification, modernism has led to a violent break leading to an extreme simplification.

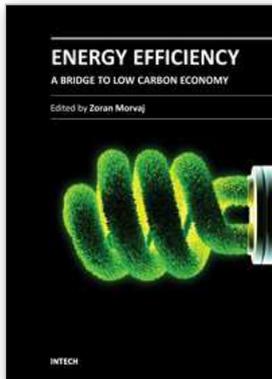
The major problem of the contemporary city is the disconnection between scales. The 20th century technician urban planners who ignored the fractal structure of historical cities divided the city into two spatial scales dedicated to two types of relations and behaviours: the greater metropolitan region traversed and structured by large transit infrastructures dedicated to speed and summarily zoned; and the neighbourhood, celebrated as the building block of the sustainable city, when its concept, boundaries and limits remained blurry and ill-defined. Two stances were adopted as a result. The first involved razing the old fabric and inordinately enlarging the urban grid to bring it in line with the major regional thoroughways. This was the position taken by Le Corbusier (Le Corbusier, 1942), modernism and the new towns in France. We know today that this approach is a failure, that it engenders inhuman cities, entirely given over to speed and to the ever-growing intensification of transports and energy consumption. This floating city, drifting in a territory that is too big for it, loses all urbanity, all identity, and all definition. It stops being a city. In this sense, the 20th century will have been the century of the demise of cities. The innovative insights coming from recent scientific breakthrough presented in this chapter allow extending this thought in a more quantitative way. The reductionist approach associated with modernism has not only led to a dehumanization of cities. It has also led to structurally inefficient urban tissues. Modernist planning has been unable so far to grasp the complexity of historical urban structures that make them be climaxes of efficiency, of interaction between people and of value creation.

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 authors call urban resilience – a complex concept related to the permanence of a memory at once social, symbolic and material. Partly because

of their leaf-like structure and of their extremely high level of redundancy, the vast majority of historical cities is resilient and has managed to survive the centuries, often outlasting the civilizations that built them. Cities worldwide will be confronted to various types of perturbations and shocks in the century to come. Will modernist cities manage to survive the century and hold out against the growing risks linked to climate change? How will their structure evolve and behave if confronted to a rise in prices due to natural resources scarcity? This adaptation ability, or resilience, that is rarely –if not never – taken into account in urban policy processes, should be given the attention it deserves.

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Energy Efficiency - A Bridge to Low Carbon Economy

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Energy efficiency is finally a common sense term. Nowadays almost everyone knows that using energy more efficiently saves money, reduces the emissions of greenhouse gasses and lowers dependence on imported fossil fuels. We are living in a fossil age at the peak of its strength. Competition for securing resources for fuelling economic development is increasing, price of fuels will increase while availability of would gradually decline. Small nations will be first to suffer if caught unprepared in the midst of the struggle for resources among the large players. Here it is where energy efficiency has a potential to lead toward the natural next step - transition away from imported fossil fuels! Someone said that the only thing more harmful than fossil fuel is fossilized thinking. It is our sincere hope that some of chapters in this book will influence you to take a fresh look at the transition to low carbon economy and the role that energy efficiency can play in that process.

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