Chapter 2
The City as a Complex Thermodynamic System

Federico Maria Butera and Massimo Palme

2.1 Introduction: Non-equilibrium Thermodynamics and Complex Systems

Cities are complex adaptive systems, which means, under a thermodynamic point of view, open systems far from equilibrium, continuously importing energy, matter and information and dissipating heat as a result of energy transformations taking place inside of system boundaries (Filchakova et al. 2007). The process results in a "metabolism" of the city, in analogy with natural living systems (Wolman, 1965; Kennedy et al. 2007; Zhang et al. 2015). In physics, a system is defined as "isolated" when it does not exchange matter and energy with the environment. A system that exchanges only energy is defined as "closed" and a system that exchanges both matter and energy is defined as "open". Open systems depend on the fluxes of matter and energy that move through them. The branch of physics that studies the theory of this kind of systems is the non-equilibrium thermodynamics, which considers the system as time dependent. Simple open systems are often near the equilibrium, or in a quasi-steady state. On the other hand, complex systems—which are alive and continuously evolving—move far from equilibrium, where new behaviours emerge. A most important contributor to the development of far-from-equilibrium thermodynamics was Ilya Prigogine (1984), who introduced the concept of dissipative systems to explain the emergence of order out of chaos. However, the first idea with respect to such systems' fundamentals came from the researches on the concept of living systems done by Erwin Schrodinger (1944). In this chapter we follow the

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F. M. Butera
Politecnico di Milano, Milan, Italy
e-mail: federico.butera@polimi.it

M. Palme (✉)
Escuela de Arquitectura and CEITSAZA, Universidad Católica del Norte, Antofagasta, Chile
e-mail: mpalme@ucn.cl

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entropy approach to explain the dynamics followed by cities in their expansion and evolution as complex adaptive systems. Entropy has been found to be quite useful in the study of urban systems, because of the complementary means of the concept, coming, respectively, from thermodynamics, statistical mechanics and information theory (Purvis et al. 2019). Firstly, we will discuss the application of the dissipative systems concept to cities. Then, we will focus on the evolutionary dynamics of urban systems. Finally, we will study the adaptation and learning processes of these kinds of structures, concluding that cities are the result of a balance of diversity and efficiency, fluctuating between an excess of the first or of the second depending on resource availability in the environment.

2.2 Cities as Dissipative Systems

Prigogine states that a dissipative structure is a structure that produces order by self-adaptive processes. Such a structure is emergent, in the sense that new laws have to be formulated to study its behaviour, and hierarchical, in the sense that it organizes itself on different levels, responding to different functions. Living beings and ecological systems are dissipative systems. Social systems, like cities, are surely complex systems, but are they also dissipative systems? Some attempts to answer this question have been carried out in the recent past.

Lai et al. (2013) developed a model to simulate urban development and used it to predict the entropy evolution of urban structures. Their conclusion is that cities should be considered as dissipative systems, moving to low internal entropy values according to Prigogine definition. However, the author also notes that cities are not just free-running and self-organizing systems. Planning is always present to guide the adaptive process.

Portugali (2000) states that cities evolve under the pressure of different agents like urban planners and firms that design buildings and public equipment, but with results that are always different from original planning ideas and drivers. The process appears different when timescale is changed: if postmodern cities seem to evolve under planner guidelines—most of the time based on pattern recognitions (Alexander et al. 1977; Linch 1960)—the shift from rural villages to middle-age cities and then to modern urban settlements presents complex behaviour similar to an adaptive self-organizing process.

Rees (2012) evidences that cities are inserted in a more complex dynamic, which can be studied by applying the SOHO (self-organizing holarchic open) complex system theory. This model can explain the negative entropy creation of a subsystem in terms of degradation of the immediate hosting system. Rees puts also in evidence that there exist many differences between non-human and human-driven complex systems, with probably the most important fact being that the human ecosystems present an excess of catabolic processes, which are destructive instead of regenerative, like anabolic processes.

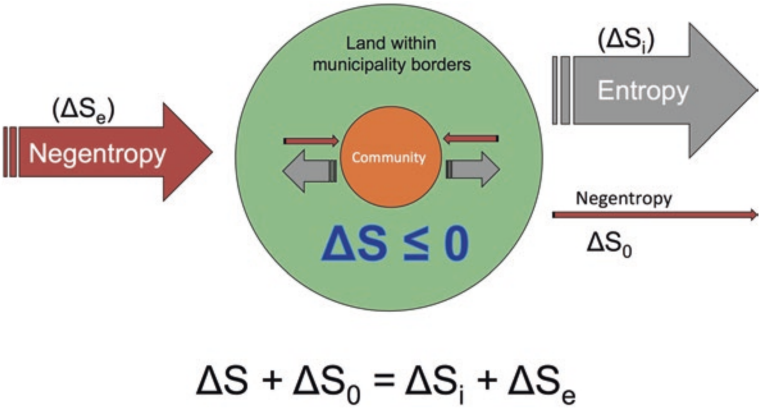

Fig. 2.1 The city as an open thermodynamic system. ΔS is the system's entropy variation per unit of time; ΔS_i is the system's production of entropy (always positive); ΔS_e is the flow of entropy coming from the environment (always negative); and ΔS_0 is the possible negentropy coming out of the system. (Authors' drawing)

One of the visible effects of such kind of destructive dissipation is the urban climate degradation. If the climate of the biosphere is able to regulate itself and adapt to changes on different scales of time, urban climate seems to be driven by humans in a no-return way towards constantly increasing heat dissipation. Urban heat island is one of the most immediate consequences of human-driven evolution of cities (Santamouris 2014; Palme et al. 2017).

Figure 2.1 presents the concept of a city as a negative entropy processor. The system imports information, matter and energy; then proceeds to internal processing of these; and is able to increase its own organization and even to export more information to the environment. The associated entropy dissipated is the price that has to be paid for the order production that takes place inside of the system.

2.3 Evolution: Between Specialization and Diversification

Complex systems evolve in a circular manner, moved by two very different principles—so different that it could be regarded as apparently opposite. The first is the principle of the minimum entropy, proposed by Nicolis and Prigogine (1977): an evolving system constantly tries to put itself in a local equilibrium point where entropy production is minimized. This principle relates to the efficiency of energy transformations, as noted for example by Labanca (2017). The second principle is the maximum power production (Odum and Pinkerton 1955), expressed also in terms of maximum exergy dissipation (Morowitz 1979): an evolving system should develop itself generating a variety of different solutions or capacities to respond to external solicitations. In the aforementioned study, Labanca states:

> […] in a condition of energy supply limitation and quite stable boundary conditions, system structures and components requiring a lower energy input to produce a given output have a competitive advantage and will prevail over less efficient ones (i.e. over system structures requiring more energy to produce a same output) determining a system transformation that can be characterized in terms of an increased organization. This reorganization causes therefore a lowering in the diversity of options available to perform a same function in the short term and may put system survival at risk in case of a change in the boundary conditions. On the other hand, it contributes to liberate energy whereby the activity within more efficient structures can be focused and intensified so making the whole systems more robust and capable of generating new diversity in case a new condition of energy abundance will be achieved.

It seems finally that complex systems evolve under both principles with the objective to eliminate the most inefficient processes and at the same time to generate a variety of possibilities to adapt to changing external situation. The predominance of one principle or another is set by the availability of external resources: if the environment is rich of resources the evolution will privilege the creation of diversity, while if resources start to be scarce, then evolution will privilege the efficiency of a hierarchical order. So, ecosystems will constantly move in this oscillation between biodiversity generation and species specialization (Fig. 2.2). Glansdorff and Prigogine (1971) called that “thermodynamic fluctuations” and suggested that the probability of occurrence of such events is directly linked to the distance from equilibrium of the systems, which should be assumed as an indicator of the state of far-from-equilibrium systems, just like temperature is assumed as an indicator of the state of a system in equilibrium. Thermodynamic fluctuations should have caused, following this interpretation, the numerous massive extinctions and the periods of species growth occurred on the planet Earth. A similar interpretation was also proposed by Cavallaro (1998), who identified a loop of growth and decline of urban systems through urbanization, suburbanization, deurbanization and re-urbanization phases.

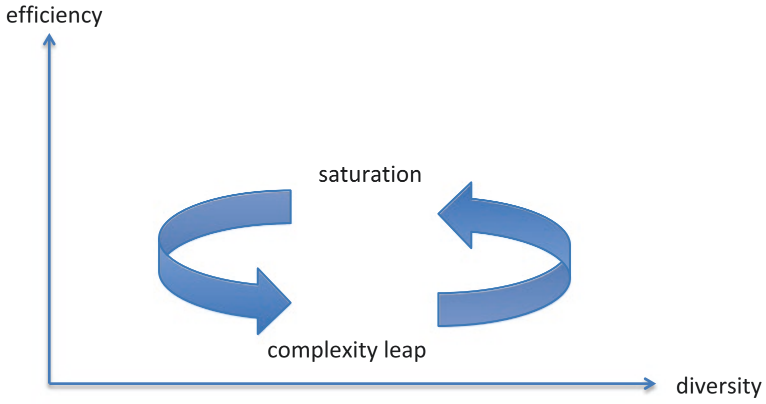

Fig. 2.2 Complex system dynamics from growth to saturation and complexity leap (a change in boundary conditions that enables new diversity explosion). (Authors’ drawing)

2.4 Adaptation and Autopoiesis

Dissipative structures are adaptive systems. Such kind of systems depend on incoming matter and energy flows and cannot avoid outgoing residuals. A dissipative structure is not a stand-alone one: on the contrary, it is strongly dependent on the environment. However, as order is extracted out of chaos, a dissipative structure has to be considered as autopoietic, in the sense that it generates its own rules to function (Allen 1998). Labella (1998) proposed different modelling approaches to describe such kind of systems, the most important being the perturbation theory approach, the fractal approach and the catastrophe theory approach. Each of these approaches is useful to describe some characteristics of complex systems like cities. The perturbation theory shows that small changes in boundary conditions can lead to bifurcations and increasing consequences. Fractal approach puts in evidence of the existence of scaling laws that should be studied in topological sense. Evidences of scaling effects in cities are numerous (Isalgué et al. 2007; Bettencourt et al. 2007; Li et al. 2017). The catastrophe theory approach underlines the occurrence of external and unpredictable events pushing the system into new states. As a consequence, it is fundamental to understand the importance of resilience in urban studies.

Even if it may seem that they are similar, there is, instead, a large difference between ecological systems and technological or social systems. Adaptation process of the latter ones is not really a free self-adaptation process. They evolve using guidelines, normally by imitating other structures that are functioning somewhere.

Butera (1998) proposed the concept of “guided self-organization process” to describe the way in which cities evolve. This kind of process takes place as a learning process on the basis of the communication between the subsystem and the hosting system, to use the Reese conceptualization, or between the system and the environment, to use a more common way to express the same.

It can be appropriate to use, for cities, information theory methods, particularly in the formulation done by Jantsch (1980), who focused his work on the pragmatic information. Pragmatic information is a kind of information that generates changes in the receiver. In other words, it is a newly discovered negentropy, recognized and metabolized because of structural changes in the system. If we conceive the city as a negentropy processor, like exposed in Fig. 2.1, we can conclude that the evolution of such a system is only possible by recognizing new things as resources. Changes in the system are structural changes when something that was only noise before the change is now appreciated as a useful resource for the system metabolism. Pragmatic information can be regarded indeed as a balance between novelty and confirmation. The ability to recognize new resources, or to assign value to resources that was not considered before, comes out of the noise through a communication process that uses pattern recognition as a driver, according to the hypothesis developed by Haken and Portugali (2003). The new information is interpreted as a message, depending on the ability of the system’s actors to analyse other structures and recognize relevant patterns. This is exactly the guide-learning process that permits self-organization of urban systems.

During a transition between states of the system, the novelty component overpasses the confirmation and the entropy released by the system tends to a maximum (A). When novelty is absorbed by the system and recognized as useful information, the balance of novelty and confirmation tends to be 50% and the entropy reaches a minimum (B). This is the local quasi-stationary point in a phase space where the system will stand for a while. Kauffmann (1993) called this phenomenon "structural stability", referring to a far-from-equilibrium point that found the energy flows needed to maintain the system organization (Fig. 2.3).

To visualize the learning process, the description by Haken (1988) can be used. Patterns can be assumed as constituting a landscape, with hills and valleys. The system leads to a valley, that is, a local quasi-steady-state condition attractor. When a message comes to the system, two situations could happen. The message can be recognized as information, so the system is pushed to new attractors, or the message is not recognized as information and the system does not move from the actual state. When the message is recognized as information, the evolution to new system's quasi-equilibrium can be reached by different ways: the new attractor can be uniquely determined, or the message can give rise to different attractors. Finally, different messages can give rise to the same attractor. Not all the messages or the attractors have the same importance, of course. The redundancy of the system is determined by the quantity of messages pushing the system to one specific configuration. The evolution is a learning process that is possible only in a combination of novelty and confirmation, in terms adopted by the communication theory. Redundancy is an aspect that increases in mature systems, where efficiency is privileged with respect to power maximization and diversity explosion. However, mature systems arrive to saturation and collapse, moving the dynamic forward to new

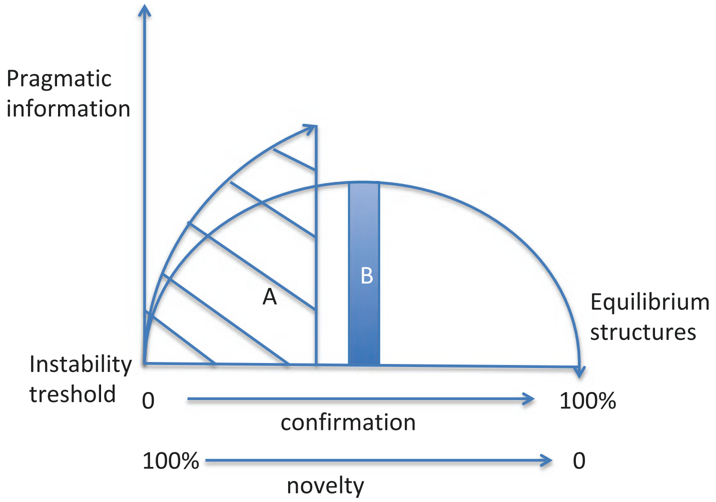

Fig. 2.3 Fluctuation novelty-confirmation and pragmatic information according to Jantsch. (Author redrawing from Butera 1998)

configurations. In this sense, the novelty-redundancy loop expresses the same dynamics of the efficiency-diversity principles exposed by Labanca.

2.5 Conclusion: The Future of Cities as a Balance of Efficiency and Diversity

Future cities should close as much as possible the circles of production and consumptions in order to lower the local entropy production but conserve sufficient diversity to assure resilience. It was timely observed by some authors (Ho 2015; Pelorosso et al. 2017), who proposed the "low-entropy city" as a structure able to pack together many metabolic processes respecting the emergency of possible adaptation strategies. It has to be observed that this vision refers to the entropy processed in the system at a certain time.

Ensuring diversity and resilience of a system implies that its efficiency is not maximized and, thus, the entropy production is not minimized. Otherwise, in systems whose efficiency is maximized entropy production is minimized. This is true in principle but not in the real systems created by humans, because of the so-called rebound effect or Jevons paradox (Wallenborn 2018; Polimeni et al. 2008), according to which each efficiency improvement gives rise to an increase in the amount of resources metabolized by the system and an increase of consumption—thus increase of entropy production.

The dynamic explored in previous sections shows that all complex systems move in a circular way, evolving through different phases from chaos to order and then to chaos again. This movement always permits the complex system to be resilient, which means to be able to reconfigure itself to adapt to changed boundary conditions.

However, we should take care of the concept of resilience we use. The dynamic described by Labanca suggests that the energy dissipated in the whole system (environment) makes it (the environment) able to generate new configurations once energy abundance would be achieved. However, such resilience concept implies the destruction of the subsystem that was critically exposed to resource scarcity. Is that the type of resilience we are looking for? It appears quite obvious that the planet Earth will be able to reconfigure itself after the eventual urban civilization collapses. But what about us? We should construct a very different type of resilience: a resilience internal to the system, that is, something able to generate the capacity of the urban structures to constantly renew themselves to respond to environmental pressure.

So, the idea could be to generate many local subsystems with high levels of energy efficiency and order, maintaining certain degree of entropy production inside the system representing the city as a whole (not just in the external environment). One of the problems is then what is defined as "external" to the system. Probably, these considerations should also lead us to a reflection on the dichotomies we still use in urban science—such as rural-urban just to name one of these. Recently, different researches expressed new vision as an attempt to overpass this dichotomy and to reach a more dialectical dialogue with nature (Inostroza et al. 2019).

Urban microclimate probably evolves under the same dynamics of the city as a whole complex system. In times of resource availability, different configurations of urban subsystems generate different microclimates. Then, the city evolves with efficiency and specialization, generating a diffuse urban microclimate. Probably, in a short future, rural-urban distinction will not be used anymore and we will live during a time in a complex urbanized world, with consequences on the macroclimate, which will evolve to a general urban macroclimate in a dissipative world. The study of the conditions that are generating today the urban climates, as well as the solutions for comfort and energy savings in such a situation, is a growing field that involves the efforts of both academia and practitioners to arrange countermeasures and build resilience in the way described before as internal adaptation capacity (Fig. 2.4).

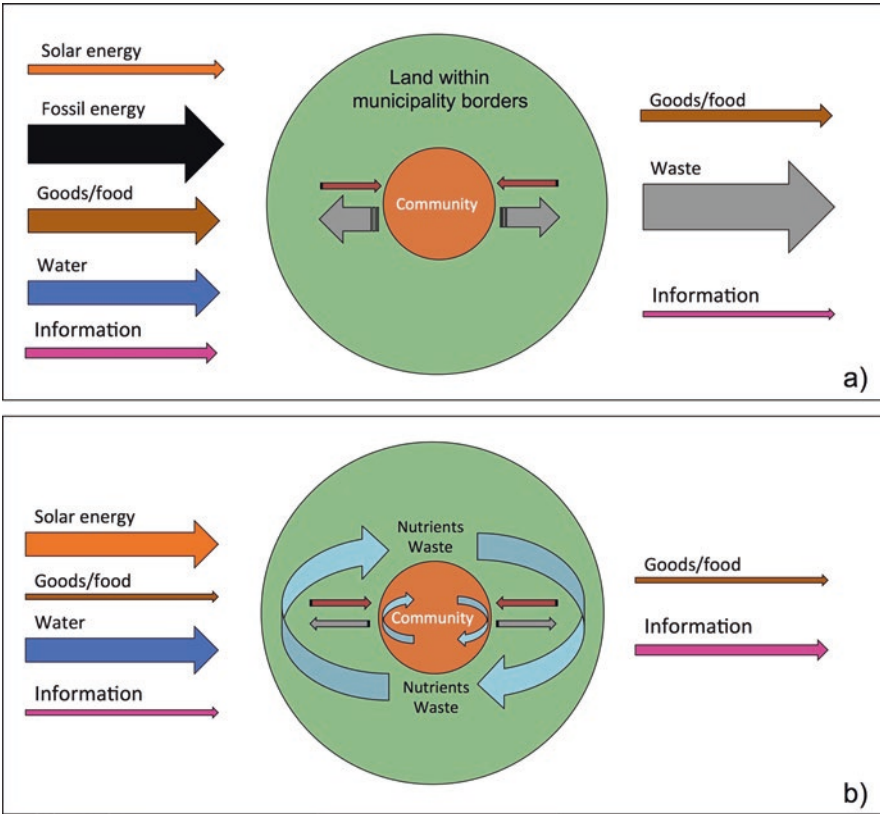

Fig. 2.4 High (**a**) and low (**b**) entropy cities. In a high-entropy city, flows are linear, required inputs are high as well as the waste is released to the environment. In a low-entropy city, the inputs' need is lowered (and fossil energy disappears), recycling and reusing contribute to close loops of materials and energy inside of the system, and waste release is reduced to almost zero. (Authors' drawing)

A combination of two objectives, in terms of metabolic change of future urban settlements, should be achieved. The first objective is to reduce the n-entropy flows but maintaining the services we need. It implies a more efficient use of natural resources and a reduction of waste. The second objective is to develop solutions responding to local stimuli that implies an increase in diversity and redundancy of the system. Sample actions to be taken are implicit in the concept of circular economy (Leone et al. 2018) and can be listed as follows:

- To decentralize energy production mainly by renewable sources (coupled with an increased energy efficiency of building and industry sector)
- To improve the efficiency of transport system, substituting private-car mobility with public transportation, car sharing, walking and biking (supported by new mixed-use planning)
- To incentivize local food consumption and a proper return of organic waste in the soil
- To optimize water cycles introducing new uses for waste water
- To reduce material flows through maintenance, repair and reuse of any kind of goods

All these actions imply not only an increase in the efficiency of resource use, but also a change of lifestyle, focusing on local diversity and avoiding the alienated cycle of production and consumption of goods at a global scale. A new economical thinking is, of course, the base for the new cities' metabolism development. A deeper insight into these issues is required, involving all disciplines: from physics to ecology, from economics to political sciences, from sociology to information science. Otherwise, without any tool for planning sustainable and resilient cities, there is a high risk of total collapse of their present structure and rise of new degraded ones.

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