Can the Mechanisms of Self-organization Help our Cities in Following the Scaling Laws of Biology? The International Conference on Artificial Intelligence: Position Paper

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Abstract— *In this paper, we discuss the growth of our urbanized cities as a scalable dynamic process. Cities represent complex adaptive systems, which are able to survive over time while continuously growing. This leads to a set serious and alarming consequences. In this paper, we attempt to characterize the complex networks of cities modeled as self-organized systems, and exploiting the self-organizing mechanisms in proposing techniques to control the dynamics of the city's growth.*

Keywords: Scalability; Growth of cities; Self organization.

1. Introduction

Scalability is a fascinating characteristic of a wide spectrum of natural, physical, chemical, and biological systems, which helps these systems to, both, adapt and survive. Complex systems can demonstrate scalability at scales of different types such as time, space, and size as well as at different levels from systems with characteristic scales to free-scale systems. In this paper, we shed light on the scalability associated with the emergence of our urbanized cities. According to UN-Habitat, 2009[1], it was estimated that 3 million people are moving to cities *every week*, around the world. This migration is a result of the long list of attractions offered by the cities in terms of services, products, and life standards. Nevertheless, such a high rate of migration leads to serious consequences that are affecting the life on our planet on its different scales from the individual scale up to the planet's global scale e.g., earth pollution and the global warming. Therefore, efficient mechanisms are required to help on the long term in maintaining a good survival level in our urbanized cities as well as on our planet, in general.

On the contrary, such negative consequences were avoided by other complex systems, which show a high level of scalability and are adaptive to changes at different scales. A prominent example of these systems is provided by biology. The main requirement for a biological system to grow is energy. However, in biological systems the dynamics of the growth process (scaling) is governed such that the consumption of energy is regulated over the age of the organism. This kind of regulation allows to save on, both, the energy input and the waste output. This characteristic makes of biology an important source of inspiration for developing scalable systems that are able to optimize their growth process in terms of the resource limitation and the entropy generated.

Biological systems, on the other hand, are self-organized systems—no external control is leading the behavior of their individual components. This individual behavior is the ground on which the global organization observed at the system level emerges. Self organization results, in general, from the combination of three mechanisms: (i) positive feedback,(ii) negative feedback, and (iii) fluctuations. Positive feedback and fluctuations help the system being adaptive, through providing it with the capability of exploring its state space and, hence, switching between the different states. While, negative feedback helps the system to stabilize at its specific state [1]. Systems that have a higher dose of negative feedback are, in general, not adaptive. However, systems which have a higher dose of positive feedback can reach chaos while jumping from a state to another. An optimal situation of a fully adaptive system would incorporate a balanced combination of positive and negative feedbacks. In this paper, we aim to exploit these mechanisms of self organization in proposing artificial control techniques, which helps in tuning and controlling the growth of the complex adaptive systems of our cities.

In this paper, We first give a brief insight of growth in biology in Section 2. The same process, however, in the complex systems of our cities is presented in Section 3. In Section 4, we introduce our proposal of cities modeled as self-organized systems and the main mechanisms of self organization which can be configured at, both, the individual and global level to control the growth of cities. The paper is concluded in Section 5

2. The growth in biology

Biology represents a metaphor and a source of inspiration for a wide range of scientific fields such as economy, social sciences, artificial intelligence, and others. Mechanisms and

[1]https://unhabitat.org/books/state-of-the-worlds-cities-20082009-harmonious-cities-2/

techniques inspired from biology were used to interpret an enormous number of phenomena in many fields. Furthermore, biology has helped to develop artificial intelligence and complex systems that are able to adapt, scale, and self organize. This illustrates the key role biology plays in, both, the understanding and the development of complex systems. In this paper, we exploit a particular process in biology, i.e. the growth (scaling) of biological systems, to learn its dynamics and mechanisms, in order to develop similar dynamics for artificial complex systems such as cities.

In order to describe growth in biological systems, let's take a closer look on a particular subsystem, i.e. animals. Animals in nature (including humans) spread over a large range of, both, sizes and types. Albeit this variety, one fascinating and extraordinary feature of these systems is referred to by the *Kleiber's law*. This law characterizes the energy required per time unit for a specific animal to survive as a function of its body mass. The remarkable result of this law showed a linear relationship between the required energy and the mass of the body of any particular animal. These animals have evolved following the rule of natural selection, each with a unique history of its subsystems, cell types and its own genomes. Hence, it is supposed that the level of energy required per time unit to keep any of these kinds alive should be quite random and different from the others. Nevertheless, it was a linear relationship in respect to the mass of the animal's body. This allows us to conclude that, those different animals (complex systems) are just scaled versions of each others in terms of energy consumption. The surprising part of the result is that the linear relationship is sub-linear, i.e. the slope of the line that describes the amount of energy per time unit for a specific mass is $3/4 < 1$. This means that doubling the mass of an animal makes it needs 75% more energy in order to survive. The fundamental reason behind this interesting description of scaling followed in biology resides in the networks that underly the biological systems. In general, any collective complex system can be characterized by the interactions among its different components. These interactions are translated in terms of specific networks, which can vary in their functionality, as well as in their type of nodes or links, however, the dynamics of complex systems evolve always as a result of the interactions flowing upon the underlying networks. For the growth process of biological systems, such networks are used to transfer the required energy to the cells of the organism. This energy is used in two main tasks (i) maintaining and repairing the existing cells and (ii) generating new cells (i.e. the organism grows).

While the organism is growing, the pace of life slows down and the energy needed per organism decreases. This is what is translated mathematically by the sub-linearity in the Kleiber's law ($3/4$ slop). The missed part of the energy intake slows down the process of growing new cells until it stops, and the organism stops growing. Afterwards, the further lost part of the energy intake slows down the process of maintaining and repairing the existing cells, thus the organism dies at some point. This whole biological metabolic process is supposed to help in maintaining the energy level consumed per organism's life and simultaneously the entropy level generated. The growth dynamics of biological systems represent an optimal solution for,both, maintaining energy and minimizing the output of the entropy. Therefore, in this paper, we aim to propose some theoretical techniques and tools that can help is integrating similar dynamics in the growth of artificial complex systems, specifically cities.

3. The growth of cities

Cities don't die, they always survive [2]. Except of some classic examples such as throwing a bomb on a city or experiencing a natural disaster, cities are complex adaptive systems that grow continuously and manage to survive over time. Similar to biological systems, cities are built up of a large set of networks that underlie the different dynamics emerge in cities and facilitate their growth. Nevertheless, if we take a closer look at those networks, we can notice that their basic nodes are always the humans, either on their individual level or as communities and organizations, e.g, economic networks, social networks, educational networks, and others. The growth of these networks relies on different kinds of resources such as money, creativity, productivity, However, all these can be translated in the term of energy on a more abstract level (sometimes referred to as the social energy).

While the city grows, different life properties can be measured with respect to its growth. In this paper, we categorize those properties in (i) human-related properties, those are the properties, that have the human as their unit over which the property is measured such as wages, number of crimes, diseases, and others. (ii) infrastructure properties, those are the properties that don't have the human as their basic unit, examples include the number of fuel stations, number of bus stops, etc. For the human-related properties, we differentiate between positive properties—those which improve the life standards—and negative properties, on both, the individual and the global levels. A common remark when analyzing the dynamics associated with the growth of the infrastructure properties is that the size of those properties grows in a *sub-linear* manner in respect to the size of the city's population, which is similar to the growth dynamics of biological systems. Whereas, the growth of the human-related properties in respect to the growth of the city's population size is *super-linear* [3], [4].

This result was observed in cities over all the world, which supports the university[2] as a main characteristic of the growth of complex systems including our cities [5]. It

[2]Universality is sharing particular properties between systems at different scales, independently of the dynamical details of those systems.

was shown that doubling the size of a city's population, regardless of which city it is, saves 15% on the size of the infrastructure, and allows to gain 15% on the human-related measures (the positive as well as the negative). The theory of university in social networks allows to test that rule through analyzing any size of a city's social network and find out when doubling that size that the growth of the particular property is having an added value of 15%, e.g., the size of cellphone calls in [6].

The super-linear slope of the scaling process of the human-related properties with respect to the city's growth leads to accelerate a large range of other processes, which are associated with that growth. Theoretically, this system is going exponentially until the required resources are terminated. In this case, the system collapses since no enough resources are available to sustain an open-end system. This is the main reason why we, humans, are in a continuous search for energy resources, new technologies, new invocations that allow to provide enough resources on different scales (e.g., economically, socially, etc.) to prolong the time the system is going to survive. In other words, in order to be able to maintain an open-end growth of the complex system that is characterized by a the super-linear scaling, we need to have an infinite accelerated cycle of resources innovation. The human history supports with a lot of examples of those innovations such as coals, precious metals, computers, Internet, and others; and shows how the period between the consecutive innovations get considerably shorter over time (acceleration).

Nevertheless, maintaining the growth of cities with super-linear scaling factor has serious consequences that are tightly related to a set of problems we are confronting in our daily life such as pollution, global warming, epidemics, and others. According to the second law of thermodynamics, the entropy of a natural process that cannot be reversible, always increases (i.e. positive change). For our cities, this mean that the continuous process of growing the size of the cities, even if it helps to produce a gain for the positive human-related properties such as wages and innovations, it leads to alarming consequences for the negative properties. These consequences can be referred to by the general term of *socioeconomic entropy* [7]. Therefore, an efficient solution that can control and tune the undesired super-linear growth is the subject of discussion in this paper.

4. Cities as self-organized systems

Self-organization is the spontaneous global order that emerges in systems of all scales from galaxies down to molecules. It results from the local interactions among the individuals that build up those systems and without any central control [8]. Since, the dynamics of our cities is characterized (as mentioned above) by the different kinds of human networks, Self organization can be used as a valid model to capture the dynamics of such complex networked systems. This model emerges from the incorporation the three main components of: (i) positive feedback, (ii) the negative feedback, and (iii) the fluctuations [9]. These components are used to model the behavior of many natural and biological systems. One remarkable feature of those self-organized systems is the dynamics followed by the growth of their populations.

In this paper, we focus on a well-known model for population growth in biological systems, that is the logistic growth model. The logistic growth model characterizes a population that grows eventually to reach the limits of provided resources such as the food supply, i.e. populations cannot grow indefinitely. In [10], the authors have illustrated the role that positive and negative feedbacks play in controlling the dynamics of the system's growth in such a way that the system stabilizes at a specific upper limit. The logistic growth model can be defined by the following equation:

$$\frac{dP}{dt} = rP(K - P), \tag{1}$$

Figure 1 illustrates the domination of the positive feedback while the system is growing, but still far from reaching the limit of its resources. Over time, the negative feedback starts to take over in order to slow down the pace of the system's growth until the size of the population stabilizes at a global state, which satisfies the amount of resources available in the system. The dynamics of the logistic growth

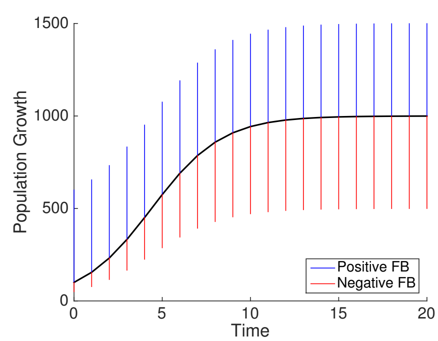

Fig. 1: The interplay between the positive and the negative feedback loops in the logistic growth model.

model represent an optimal dynamics for the desired growth of most artificial systems, including our cities, because of the limited resources available and the over production of negative consequences a super-linear growth. In case the logistic growth model is achieved for our cities, the growth of a particular city will stop when the limit of the resources required to support that growth is reached. This will restrict the growth of the city, however, and the most important will limit as well the entropy (i.e. the socioeconomic entropy) produced.

In general, self-organized collective systems can be defined through a set of global states at which the system can reside. Those states represent different types of attractors and based on their specific type, the kind of the feedback (either positive or negative) is determined. The two main types of attractors are: (i) the stable attractor and (ii) the unstable attractor. When the global state of the system represents an unstable attractor, the feedback that applies at that state is a positive one. Positive feedback pushes the system away from that state and helps in making it explore other states in the state space. Whereas, states that act as stable attractors apply negative feedback, which influences the system to stabilize at that state and leaves it becomes possible only under the influence of fluctuations or a stronger positive feedback applied at the same state. Fluctuations in this case provide the system with a random behavior that can be described as a little circle of chaos, which allows the system to explore out of its stable state and visit other states (stable or unstable).

In the collective systems that describe our cities, the different cities can represent the global states, among which the system can jump. The solution we are proposing—on an abstract level—for discussion in this paper, is to define a dynamic type associated with each global state (i.e. a city). A dynamic type means that the city can change its state (the influence this city exerts on its population) from being an unstable attractor to the state of being a stable attractor, when a particular growth of that city is reached. When the city represents an unstable attractor, it motivates the system for a *continuous change* (i.e. positive feedback). This continuous change is translated in the terms of growing the city's population. As soon as the growth of the city reaches near to the limit of resources available, the city switches to representing a stable state that tends to sustain and keeps its population size *unchanged* (negative feedback). The change of the type of the attractor, which a city demonstrates, should emerge from the interactions on the individual level between the people, organizations, and communities, which build up the underlying network of that city. This goal is associated with what is well-known as the macroscopic-microscopic link—the link between the behavior of the system on the individual level and the emergent behavior on the global level. The definition of this link such that a desired macroscopic (global) behavior is achieved is one of the most challenging tasks in defining collective self-organized systems[11], [12]. The macroscopic behavior, we aim to achieve in our city systems, is the emergent type of the attractor the city demonstrates. The microscopic behavior, in this system, is the dynamics of the individuals' (organizations or communities) interactions that lead to the city to demonstrate that specific type of attractor. Examples of system components that can play a role in defining such rules at the individual level can include: costs and/or availability of, both, services and products. For example, increasing taxes at the individual level with the increment of the population size, restricting the real estate with the increment of the population size, increasing the pollution penalties with the increment of the population size, and others. Proposing exact methods, laws, or rules that may lead to control the feedback loops that define the dynamics of a self organized city system is out of the scope of this paper. This paper, aims only to shed light on the theoretical ground for analyzing and controlling the growth dynamics in complex systems, here, cities.

5. Conclusion

In this paper, we have focused on the problem of the super-linear growth of human-related properties with respect to the population size in our cities. The super-linearity of this growth leads to a set of alarming consequences, examples include pollution, epidemics, global warming and others. We have highlighted self organization as an underlying model of the city's interaction networks. Furthermore, we have proposed to exploit the main mechanisms of self organizations in controlling the dynamics of the cities' networks, in order to limit the growth of the human-related properties according to the available amount of resources. This may lead to limit the production of social entropy as well, which is one of the most dangerous consequences.

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