Urban planning and scaling in the modern city

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ABSTRACT: The complexity and the interrelations in modern urban spaces are difficult to analyse in a way that allows a rationale to improving living conditions or help to ascertain optimal decisions for saving energy or improving sustainability. Carefully designed decisions and guidelines might produce unexpected results because of particularities, or complex sets of reactions from residents or economic counterparts. Also, complexity tends to increase with size, such as when, for instance, services tend to concentrate in large agglomerations, and transportation needs take on critical importance. Complex systems such as living organisms are known to follow approximate relationships as scaling laws between the variables that describe them. These laws are believed to hold because of constructual reasons –optimization of systems that maximise flows-, or because of optimisation of resources by living species, bounded by their structure and functions, independently of particularities, mainly because the living organisms have highly organised nervous, respiratory, digestive and circulatory systems, which are the result of evolution and optimisation through natural selection. Some of these kinds of relationships are tested in relation to modern developed urban spaces, in which it is possible to find a reasonable continuity with the types of scales seen in living organisms, and some preliminary conclusions are drawn.

Keywords: complexity, scaling laws, scaling in cities

1. Introduction

Urban planning in large cities is a formidable challenge, because of the range of previsions that must be taken into account. The complexity and the interrelations in modern urban spaces are difficult to analyse in a way that allows a rationale to improving living conditions or help to ascertain optimal decisions for saving energy or improving sustainability. Large cities have a high degree of complexity and strong interrelations among their inhabitants and surroundings. Carefully designed decisions and guidelines might produce unexpected results because of particularities, or complex sets of reactions from residents or economic counterparts.

Complex systems such as living organisms are known to follow approximate relationships as scaling laws, or allometric scaling laws, between the variables that describe them. These laws are believed to hold because of constructual reasons –optimization of systems that maximise flows-, or because of optimisation of resources by living species, bounded by their structure and functions, independently of particularities, mainly because the living organisms have highly organised nervous, respiratory, digestive and circulatory systems, which are the result of evolution and optimisation through natural selection. Accordingly to [1], the scaling observed in biology is typically a simple power law: $Y = Y_0 M^b$, where Y is some observable magnitude, Y_0 a constant, and M is the mass of the organism. The exponent b usually approximates a simple multiple of 1/4. Among the many fundamental variables that obey such scaling laws are metabolic rate, life span, heart rate, mass of cerebral grey matter, and others [see 1 and references therein]. The metabolic rate for mammals and birds was shown to scale as $M^{3/4}$ many years ago for four orders of magnitude in mass, and the work was generalised by subsequent researchers to other systems, and, with some particularities, the metabolic exponent $b \approx 3/4$ is found across nearly 27 orders of magnitude in life [1].

It can be proposed that scaling laws and the generic coarse-grained dynamical behaviour of biological systems reflect the constraints inherent in the universal properties of such networks. The formidable quest for optimisation of transport (of matter, energy and information) might be considered as giving rise to scaling laws in the actual level. Also, the constructal theory states that every flow system evolves in time so that it develops the flow architecture that maximizes flow access under the constraints posed to the flow. It has been quite successful in justifying allometric scaling laws [2], global circulation and climate characteristics [3], and even scaling effects in running, swimming and flying [4]. We keep the main idea that even very complex systems, transports conditioned, as living organisms, should follow some scaling laws, at least approximately.

Even though cities seem quite far from living organisms, some general activities take place in both of them, with transport playing a crucial role: among these activities one finds transforming energy, transporting and transmitting energy, information and goods, and repairing damage to some amount. Furthermore, if biological scaling laws are the consequence of the above constraints and optimization of transport, modern, developed cities are also subject to some of these kinds of network-related constraints, even though the classes of complex networks of cities might differ from those in living organisms, giving rise to distinct patterns of connections among nodes. Even if it is the case, [5] indicates that detailed structural features cannot be captured by means of studying global properties. Thus, it seems reasonable to try to compare the gross behaviour of modern cities with the biological systems, even if this is only a first approach to more detailed considerations as an open way for further considerations. A first approach was intended in [6]

Research on scaling in cities has also been done for the structure of the city. The aim in [7] is on the structure of the plan of cities, and the scaling of lengths. [8] is also concerned with the near-fractal characteristics of cities and transport in them. Furthermore, urban supply networks have been shown to follow scaling laws [9]. In the fig. 3 of [9] it is shown that, for German cities, electric energy delivered to households grows nearly proportional to the population. Other magnitudes have been shown there to scale with population in a different way. However, no trial to extend these data to allometric scaling laws was done.

The general scaling laws followed by living organisms are herein explored to be extrapolated to the dimensions of the modern city, even though looser relations are to be expected, as there is a large difference in history (cities are much more recent than living organisms) and statistics: living organisms as animals are usually composed of a very large number of elemental blocks (cellules), compared with the inhabitants in a city.

2. Results and discussion

To check for scaling laws, one should obtain the “mass” and the “metabolism”, or power or energy consumption of a city to compare it with the scaling law for living organisms. In fact, small cities mean usually an increase of transport cost per person and somewhat less shelter, so more power per inhabitant would be needed; large cities mean usually more infrastructure, so the ratio of mass to power might change with size. While the power consumption seems a relatively clear concept, it is not so for the mass. We consider, by comparison with living organisms, that the mass corresponds to the parts that can be replaced or repaired in the case of damage or malfunction. For cities, this would correspond to the built environment (steel, concrete and masonry) plus the machinery (cars, trains,...) and furniture, plus the animals and people in a city. We assume this to be an approach, as the boundaries or frontiers of a modern city are somewhat diffuse, and we proceed with this approach. We analyse some cities with this approach.

For the case of Barcelona (Spain), we have approached its mass from the maps given in the web of the city council [10] (section of urbanism), where it might be found the number of built floors (over and under the street level) in the map. Even if it is known that some works are always under way, and some irregularities might exist, the data is assumed to be correct to a few percent of margin. Then, the estimation of built floor area for the municipality (near 1.6 million people, from [10]) is near 2.6 10^8 m^2. The surface of streets is 1.7 10^7 m^2 (from [10]). To obtain the data for the whole metropolitan area, an approximate scaling with the number of people is assumed, as constructive typologies are not too different in the metropolitan area, some 3 million people. Then, from the building characteristics and typologies, an approximate built mass can be obtained (average building mass of 350 kg/m^2 of floor, this is a quite strong source of imprecision). The estimated mass of other built elements, basements, foundations, sewage, tunnels of the train and subway, port, airport (these are also sources of imprecision), and other services should also be included, together with machinery, cars, furniture, and animals and people, giving an estimate of around 2 10^{11} kg. Due to this points, the value is estimated to be correct to a margin between 1.5 10^{11} and 3.10^{11} kg.

The total power consumption of the metropolitan area of Barcelona may be obtained from the figures given in [11], to be a mean of near 3 10^9 W for the year 1999. However, the low growth of power (energy) consumption with time should be taken cautiously, as the original data refer to the municipality, and the growth is stronger in the surroundings (metropolitan area), and then any extrapolations are to be considered gross approaches. We think the actual value (2007) should be between 2.10^9 W and 4 10^9 W. Also it should be noted that we do not distinguish between energy uses in replacement, functioning and growth, and we can just indicate a global value, and energy expenses devoted to transport of resources to the city are difficult to take into account, producing a large uncertainty for the average power spent in a city.

Data for the smaller city of Vic (near 40000 inhabitants, half-way between Barcelona and the French border) has been processed, from the maps in [12]. The estimated mass for Vic is 2.5 10^9 kg, and the estimated average power is 6.3 10^7 W.

Maps for Grenoble, French city near the Alps, with near 400000 inhabitants in the metropolitan area, have been used, together with aerial views, to have a rough value of the mass of a medium sized city. Also, an estimation of power consumption has been done. The mass for Grenoble is then 1.3 10^{10} kg, and the estimated average power consumption, 4 10^8 W.

A rough estimation for Hanoi has been done. The mass is estimated as near 4 10^{10} kg, and the power as near 2 10^9 W. The uncertainty in this case might be higher, as the modern part has building characteristics similar to the previous cities, but this is not the whole city.

Data for Paris has been retrieved from the plans in [13]. The same methodology as that for Barcelona is applied. The estimated mass is 6.3 10^{11} kg. Also, an estimation of the power consumption for Paris has been done, as 9 10^9 W.

A rough estimations for a large modern city as New York has also been done, from maps, aerial photographs and population statistics, to compare with the other cities. The estimated mass is 1.3 10^{12} kg, and the average power 1.6 10^{10} W.

Then, the position of cities can be indicated in Fig. 1, where data for animals are also represented. The size of the dots for cities corresponds to uncertainties in mass or power by a factor of nearly ten (i.e., multiplying or dividing by 3), as this is an estimate for the worst case.

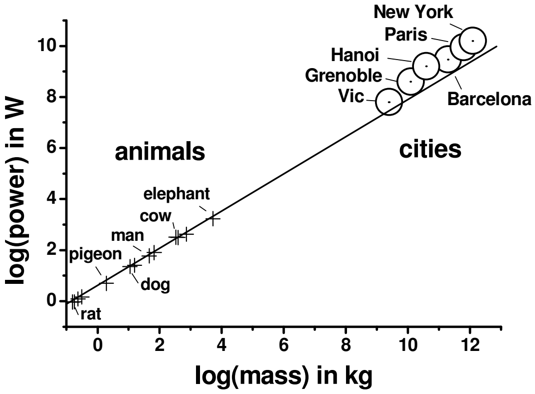

Figure 1.- Scaling law of power against mass for animals (data from [1]) and cities.

The position of the cities in Fig. 1 is quite close to the extension of the straight line traced by the data correlating to living organisms, with slope 3/4. It should also be noted that the metabolism or power used in the city lies somewhat above the straight line.

Figure 2 shows the relationship between heart rate and mass, for animals, and locates the position of some cities. Extrapolation of the straight line to the mass of a developed large city gives nearly a four-minute period for the beats (rate) of “medium” cities as Barcelona, which might be the regular changes of traffic lights (which give a pulsatory character to the major transport of mass in a city). Even though there are many pulsatory or variable with time transport activities in a modern city, the phenomenon responsible for largest mass transport is the cars and trucks movement. The traffic lights have really a period of nearly one and a half minutes in many cities (100 s in Barcelona).

If the figure really indicates an optimisation, then the actual frequency of change of the traffic lights seems to be too high for cities like Barcelona or larger. Even if lowering the frequency of traffic light changes might require solutions for pedestrians (such as elevated walkways), a lower frequency of change would increase the relative time at which the traffic moves at a constant speed, which would then enhance the optimisation of movement (less energy spent in transport). It might be recalled that after an energy crisis, it was recommended in some countries as Switzerland that cars stop their engines while waiting at traffic lights (the lights had an advice some seconds before the changes of state in cities like Geneva). The effects of these kinds of measures would be favoured by longer traffic light periods.

Further on, in biology the animal life is found to be of the order of 1.6 10^9 heart beats. If the traffic lights represent a beat for the pulsatory transport in modern cities, and this should be related to the "expected life" of a city, in the same way that in living organisms, one obtains much more than 10000 years as expected life for medium cities. In fact, in the course of history, very few cities have "dissapeared" or "dead" (as Carthago, Pompei...), so this value, even in a rough extrapolation, seems to have sense.

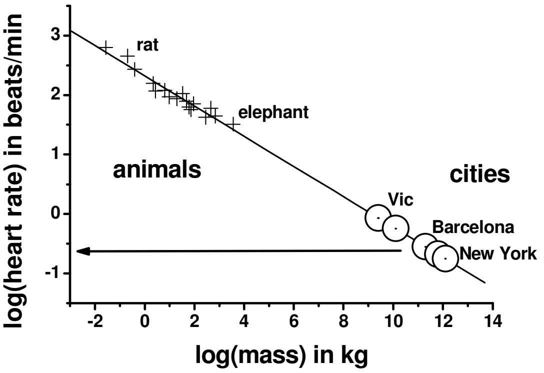

Figure 2.- Scaling of pulsatory transport frequency versus mass, data for animals (from [1]) and masses corresponding to cities, to extrapolate expected frequencies for modern cities.

3. Conclusions

A rough estimation shows that modern cities approach some of the scaling behaviour followed by living organisms. This might be interpreted as due to that both systems are essentially transport-conditioned, and optimisation of systems is under way. The scaling might be useful to take into account when looking for optimisation of some problems, transport-related. An application to timing of traffic lights is suggested

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