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Constructal Human Dynamics, Security and Sustainability

Edited by
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Constructal Human Dynamics, Security and Sustainability

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Contents

Preface and Organising Committee v

Constructal Theory and Design 1
A. Bejan and S. Lorente

Constructal View of City Flow Structure and People Safety 21
A. Heitor Reis

Flow Systems, Catastrophes, and Public Policy 37
Gilbert W. Merkx

Developing Constructal Theory as a Tool for Global Security and Sustainability 49
Wayne O. Miller

Pattern Formation and Self-Organization in Living Systems: a Unified View of Coral Colonies and Crowd Dynamics 61
António F. Miguel

Constructal Placement of Decontamination on Nuclear Waste Areas 85
Sylvie Lorente

Some Transfer Phenomena Regarding the Safety of Deep Geological Repositories of Radioactive Wastes 101
Fabien Frizon

Constructal Patterns in Air Traffic Flows and in Sustainable Information Systems 133
Stephen Périn

Constructal Flow of Education and Research 157
A. Bejan

Subject Index 175

Author Index 177

Constructal view of city flow structure and people safety

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ABSTRACT

In this paper cities are viewed as lively systems with internal flow structure of people, energy and goods. By appropriately defining concepts as metabolic rate, pulsating period, and mass previous studies have shown that cities follow known allometric laws of animals, then allowing rules for self-organization. The distributions of street lengths and nodes follow inverse-power distribution laws. That means that the smaller the network components, the more numerous they have to be. In addition, street networks show geometric self-similarities over a range of scales. Based on these features many authors claim that street networks are fractal in nature. What we show here is that both the scaling laws and self-similarity spring out of the underlying dynamics, together with the purpose of optimizing flows of people and goods in time, as predicted by the constructal law. The results seem to corroborate the prediction that cities fractal dimension approaches 2 as they develop and become more complex. Examples from History show that constructal law provides a basis for understanding the internal structure both of roman and medieval cities. Finally, it is shown that the constructal law also provides the base for the design of flow structures (street networks, corridor networks) which perform optimally with respect to evacuating people from disaster areas.

1. INTRODUCTION

Cities are very complex systems that have developed in time under the influence of multiple factors (politics, social structure, defence, trade, etc). Even though the relative weights of these factors seem to vary very much from city to city, some features have been noticed that are common to every cities. For example, it has been verified that cities possess self-similar structures that repeat over a hierarchy of scales (Alexander, 1977, Krier, 1998). This provided the basis for many authors to claim that many aspects of cities allow a fractal description (e g. Salingaros, 1995, Batty and Xie, 1996; Salingaros and West, 1999; Shen, 2002; Carvalho and Penn, 2004; Moura and Ribeiro, 2006). This observation, however does not explain why cities do share this architectural similarity. Idealists would claim that, as cities are complex man-made systems this common aspect springs out of the congenital ideas of beauty and harmony shared by mankind. On the other hand, constructal theory tells us that dynamics is behind geometry, such that geometry evolves just as the envelope of underlying dynamic processes. The constructal law first put forward by Bejan (1997) states that "for a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed (global) currents that flow through it."

Cities are living systems in the sense that they have proper "metabolism" driven by the activities of their inhabitants, are open to flows of goods and people, and evolve in time. Lanes, roads, streets, avenues constitute the vascular network of cities. As with every living system, city networks have evolved in time such as to provide easier and easier access to flows of goods and people. Street networks of today's cities tell the old story of the dynamics of the past. From the ancient to the newest district we can observe the development of streets of decreasing flow resistance, or, said another way increasing access for people and goods (Reis, 2007). The street networks of the old parts of today's cities are fossils that testify the past dynamics of the city (see Fig.1).

2. FRACTAL DESCRIPTION

Hierarchically organized structures, in the sense that a structure of dimension x is repeated at the scales rx, r^2x, r^3x, ..., where r is a scale factor, have been noticed in most of today's cities. Structure self-similarity at various scales indicates that such structures allow fractal description if some property ϕ of the self-similar structure obeys the relationship

$$\phi(rx) = r^m \phi(x) \tag{1}$$

where m is the fractal dimension. Examples of repeated self-similar structures are some patterns of street networks that look the same at various scales.

In a city the number of pieces N(X*)* of size X seems to follow an "inverse-power distribution law" of the type

$$N(X) = CX^{-m} \tag{2}$$

where *C* is a constant and $1 \le m \le 2$ (Salingaros, 2003). Therefore, if X_0 is the dimension of the city, by using eq. (1), the number of pieces of dimension $X_n = X_0 r^{-n}$ is given by

$$N(X_n) = CX_0 r^{-nm} \tag{3}$$

Therefore, the number of pieces (e.g., streets) is reduced between successive scales by the factor r^{-m}. Both r and m account for a particular spatial organization characteristic of each city. In Fig. 1 we identify the various scales of streets in downtown Lisbon, and it is easy to confirm at first glance that the number of small streets is much higher than that of larger ones.

Fig.1 - The flow system of downtown Lisbon. The huge variety of pieces (streets, laves, avenues) aggregate in coherent small (fossil) subsystems, which testify the past dynamics of the city.

The rule conveyed by eq. (3) is a distribution of geometric patterns solely, and does not make clear why city structures organize in such a way. We sustain that the reasons for such a particular distribution grounds on the underlying city dynamics.

3. FLOW STRUCTURES IN A LIVING CITY

Cities have their own metabolism that consists of people's everyday activities. People exchange and consume goods and services in the cities and, because cities are open systems, with the rest of the world. The various flows that cross the cities distribute people and goods to the proper places for daily activities.

Cities also are flow systems open to the outside. The inflows that cross the city boundaries carry energy, information, food, and other goods, while the outflows also carry information and goods, and wastes mainly. History tells us that cities have developed when and where a flow system for supplying goods and removing wastes was continuously maintained for a long period. Thus, because cities share this basic feature with living (biologic) organisms it makes sense to speak about metabolic rates and pulsating flows, as it happens with breathing and heart beat rates in animals.

3.1 Metabolic rates and rhythms of cities

The concept of city as a living organism with pulsating flows has been explores in a notable work of a team from the Barcelona School of Architecture. Actually, Isalgue et al (2007) examined power that drives city metabolism in relation with mass involved in metabolic processes, i.e. "the built environment (steel, concrete and masonry) plus the machinery (cars, trains,...) and furniture, plus the animals and people". Their results are shown in Fig. 2, together with those for animals, already published in the literature, and show that, as it happen with animals, power (city metabolic rate) scales with mass raised to the exponent ¾.

The previous result has been anticipated by Bejan (1997), by analyzing constrained heat and fluid flows in relation with animal size, based on the constructal law, and also by West et al. (1997) based on fluid tree optimization only.

Additionally, Isalgue et al (2007) studied city pulsating rhythms in relation with city mass, which they considered in the same sense as in the previous case. City flows of walkers and traffic are regulated by traffic lights which open and close with periods that in general are larger for bigger cities. In this way, the frequency of change of traffic lights provide a good indicator of pulsating rhythms, as the equivalent of heart beat rates in animals. Then, they used the known law that states that the heart beat rate scales with body mass rose to the exponent ¼, to anticipate what the optimum frequency of changes of traffic lights should be for a number of cities (Fig.3). As with the previous case this is a result already anticipated based on the constructal law (Bejan, 1997).

The previous examples strengthen the belief that cities may be viewed as flow systems whose self-organization obeys general laws deserves credit. Hence, in what follows we pursuit the objective of analyzing city structure based on the constructal law.

3.2 Modelling "rivers of people" and city traffic

By walking or by using means of transportation, people and goods flow through the inner vascular system that covers the city territory. Each of these means of transportation uses a proper channel to move in. People's movements starts being unorganized (erratic when if we consider a group of individuals) showing the characteristics of a diffusive flow, then becomes progressively organized (more and more people moving in the same ways) as people move into the larger ways. Public transportation exists because individuals agree in moving together in some direction. It is also a way of saving exergy and time. The speed of transportation increases as individuals proceed from home to the larger ways, while the inverse occurs as they approach the area of destination. This designs a flow tree that is inscribed on the city street network (Fig.4).

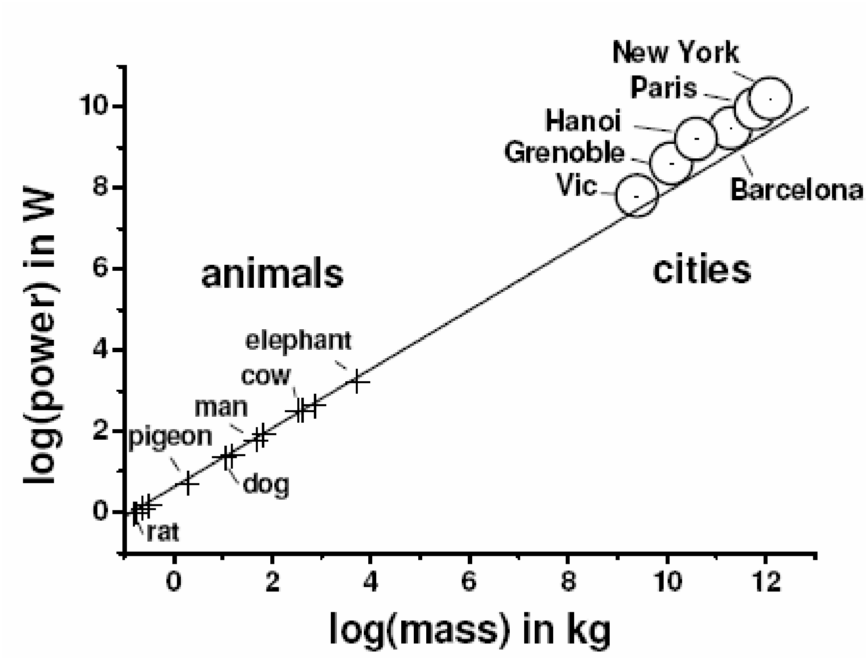

Fig. 2 Scaling law of power dissipated against mass. Cities follow the same scaling as animals, i.e. power dissipated scales with mass raised to the exponent ¾ (adapted from Isalgue et al 2007).

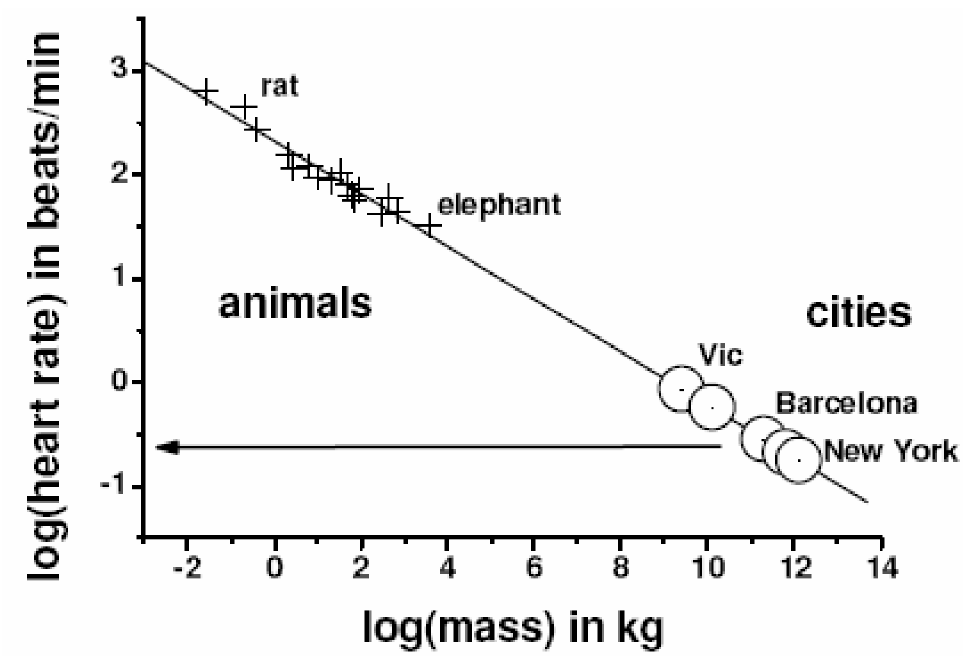

Fig. 3 Scaling heart beat rates for animals and extrapolation for the optimum frequency of changes of traffic lights for some modern cities (adapted from Isalgue et al 2007).

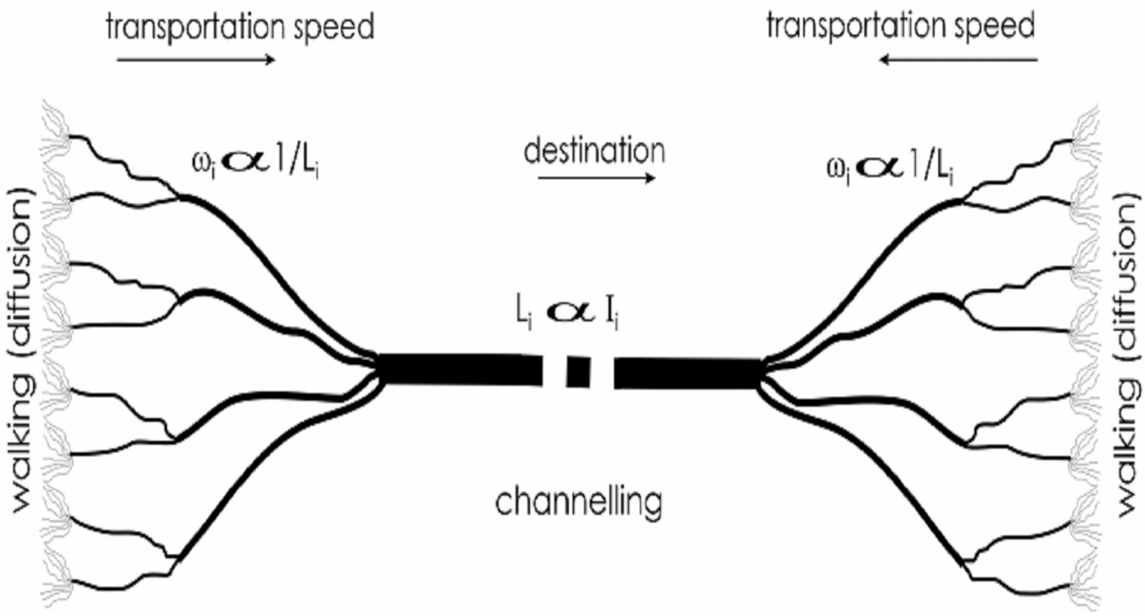

Fig.4. Area to point and point to area flows. Individuals move from one area to another by using successively faster means transportation first, this rule being inverted as they approach the area of destination.

In some aspects, modelling flows of people is not the same as modelling flows of inanimate fluids. In fact, fluids are ensembles of particles that act in a purely mechanistic way, i.e. under the action of known external forces. In the later case, the Navier-Stokes equation, which equates driving against dissipation (brake) forces, together with boundary and initial conditions are enough to predict the flow. However, in flows of people, the individuals are not only subjected to external forces as fluids are, but as living systems experience also "internal" forces, most known as desire, decision, etc. Then, how to physically model such biased forces? Actually, we cannot, but instead we can model their effect by accounting for the resultant entropy generation rate. In this way, we will be able to define the resistance to flow, precisely.

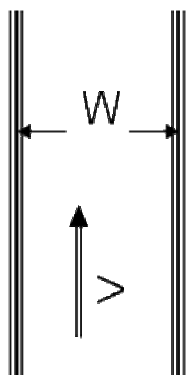

Fig. 5 Flow at average speed v in a street of width W.

For example, consider a street of width W, with spatial concentration of cars, σ (cars/m²), that flow with an average speed v (m/s) (Fig. 1). If some car proceeds with a velocity difference of order Δv with respect to the next one, then its driver has to slow down on the same Δv in order not to hit that car. Therefore, the exergy lost is the process is $\varepsilon = -mv(\Delta v)$, to which corresponds the entropy generation, $s_{gen} = -\varepsilon/T$, where T is ambient temperature (Guoy-Stodola theorem).

Let θ_i be the fraction of the number of cars in the control area W×L, with velocity difference Δv_i with respect to the next car, and let λ be the safety distance between successive cars. Then, the total number of decelerations per second in the control area is given by $\sigma \sum_i \theta_i (\Delta v_i) W L/\lambda$, while the total power (exergy/s) lost $\dot{E}_i$ is given by

$$\dot{E} = \sigma \sum_i \theta_i (\Delta v_i) W (L/\lambda) m_i v (\Delta v_i) \tag{4}$$

where v is the average speed of the cars. According the Guy-Stodola theorem, one has

$$T\dot{S}_{gen} = -\dot{E} \tag{5}$$

The eq. (5) enables us to define the flow resistance, R, as

$$R = T\dot{S}_{gen} \big/ I^2 \tag{6}$$

where I represents the car (people) flow rate in the street, which is given by

$$I = \sigma v W \tag{7}$$

According to eq. (6) the resistance to flow is proportional to the entropy generation rate per car (people) flow rate. Therefore, whatever the nature of the potential difference ΔV that drives the flow is, the end result is always exergy dissipation, $(\Delta V)I$, which balances entropy generation

$$\Delta V = -T\dot{S}_{gen} \big/ I \tag{8}$$

By considering the eqs. (4-7) the flow resistance reads

$$R = \sum_i \theta_i m_i (\Delta v_i)^2 L \big/ (\sigma \lambda v W) \tag{9}$$

It is commonly observed that the wider the street, the higher the average velocity of what flows in. We assume, as a first approach, that the average velocity is proportional to street width, i.e. $v = kW$, and therefore eq. (9) reads

$$R = \sum_i \theta_i m_i (\Delta v_i)^2 L \big/ \left(\sigma \lambda k W^2\right) \tag{10}$$

The group $\nu = \sum_i \theta_i m_i (\Delta v_i)^2 \Big/ \overline{m}(\sigma\lambda^2 k)$, where m represents average mass of cars (people) has dimension of viscosity and characterizes the "fluid" that flows in the street. Then, then by inserting ν in eq. (10) it turns into

$$R/L = \nu\lambda \big/ W^2 , \tag{11}$$

which indicates that the flow resistivity is directly proportional to the "viscosity" of what flows and inversely proportional to street width. The resistibility of the "street flows" shows the same dependence on channel width W as with "Hagen-Poiseuille flow" between parallel plates. This enables us to use the results of constructal optimizations previously carried out for river basins (Bejan, 2000, Reis, 2006a). Chen and Zhou (2006) had already noticed that the city scaling laws take the form of known laws of geomorphology, namely of river basins. What we show next is that as with the river basins also the scaling laws of city networks spring out from the underlying dynamics.

3.3 City networks and fractal dimension

Bejan (2000), optimized flow trees for area-to-point flows, of resistivity $\underline{R/L \propto 1/W^2}$, in two ways: (i) by minimizing global resistances under constant flow rate and "drainage area"; (ii) by minimizing the volume (area) allocated to channels (streets) in the tree subject to fixed global resistances and "drainage area". Reis (2006) showed that Bejan's relations anticipate known scaling laws of river basins (Fig. 6). One of such laws tells us that the ratio of the average lengths of streams of consecutive hierarchical order is constant, i.e.

$$\frac{L_n}{L_{n+1}} = R_L \tag{12}$$

where $R_N \sim 2$, while the same happens with the average number of streams of consecutive hierarchical order, i.e.

$$\frac{N_{n+1}}{N_n} = R_N \tag{13}$$

which is also a constant, $R_N \sim 4$ (see Fig. 7). Reis (2006) showed that despite the relationships (12) and (13) have been derived from constructs of regular geometry as those of Fig. 7, they are applicable to any hierarchical stream network irrespective to its particular geometry. Moreover, relationships (12) and (13) imply that they are self-similar in the range its applicability (see also Figs.6 and 7).

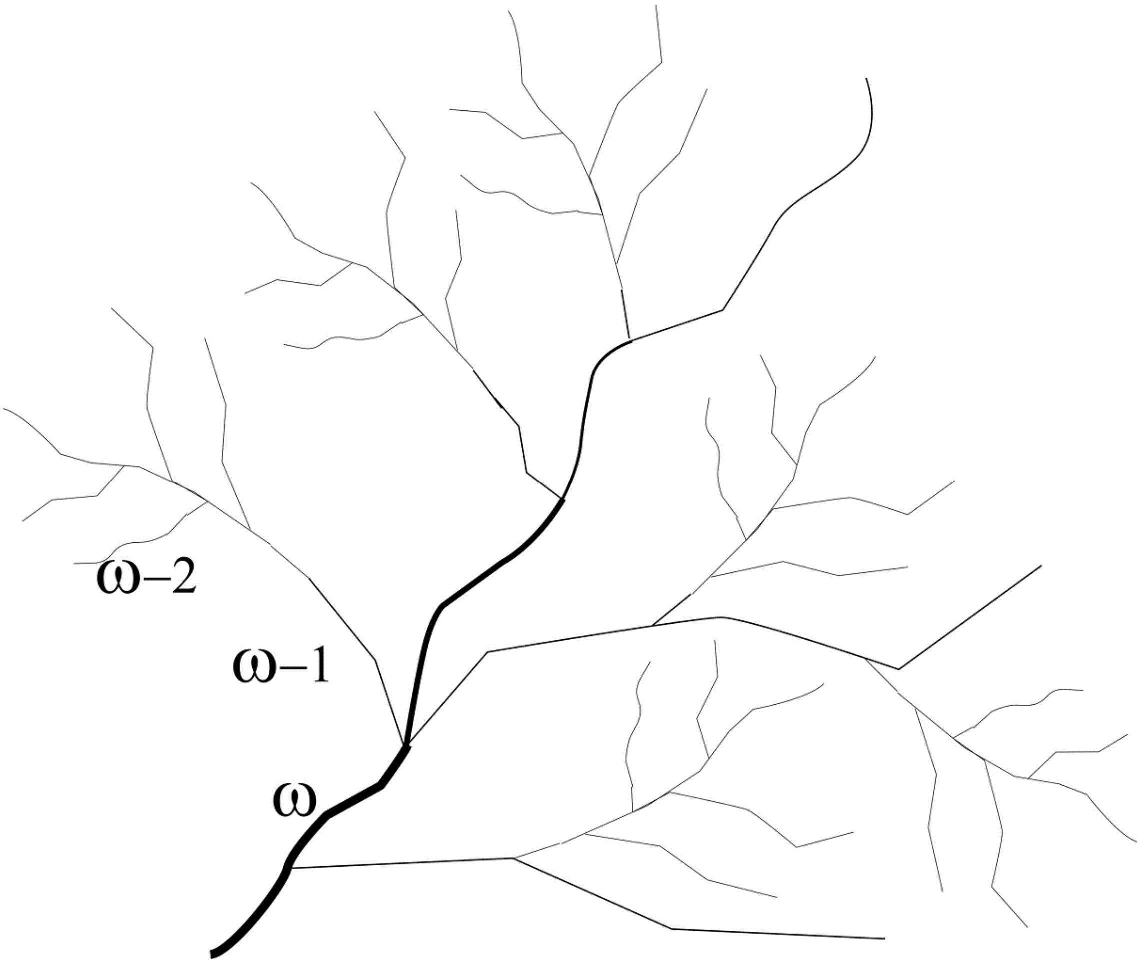

Fig.6 Flow tree that is self-similar at various scales. Note thar streams of order ω-1 are tributaries of streams of order ω.

Because these scaling laws spring out of the optimization process carried out under the eq, (11) that hold for both Hagen-Poiseuille flow and street (people) flow it follows that Eqs. (12) and (13) must also hold for the city street networks. Therefore, if L_0 represents the scale of the largest stream in the city, from eq. (12) one obtains the following scaling law:

$$L_n = L_0 / R_L{}^n \tag{14}$$

Analogously, from eq. (13) one obtains:

$$N_n = N_0 / R_N{}^n \tag{15}$$

Taking into account eq. (14), by denoting $N(L_n) = N_n$ and $N(L_0) = N_0$ and aplying eq. (1) one has:

$$N(L_n) = N(L_0 R_L{}^{-n}) = R_L{}^{-mn} N(L_0) \tag{16}$$

or,

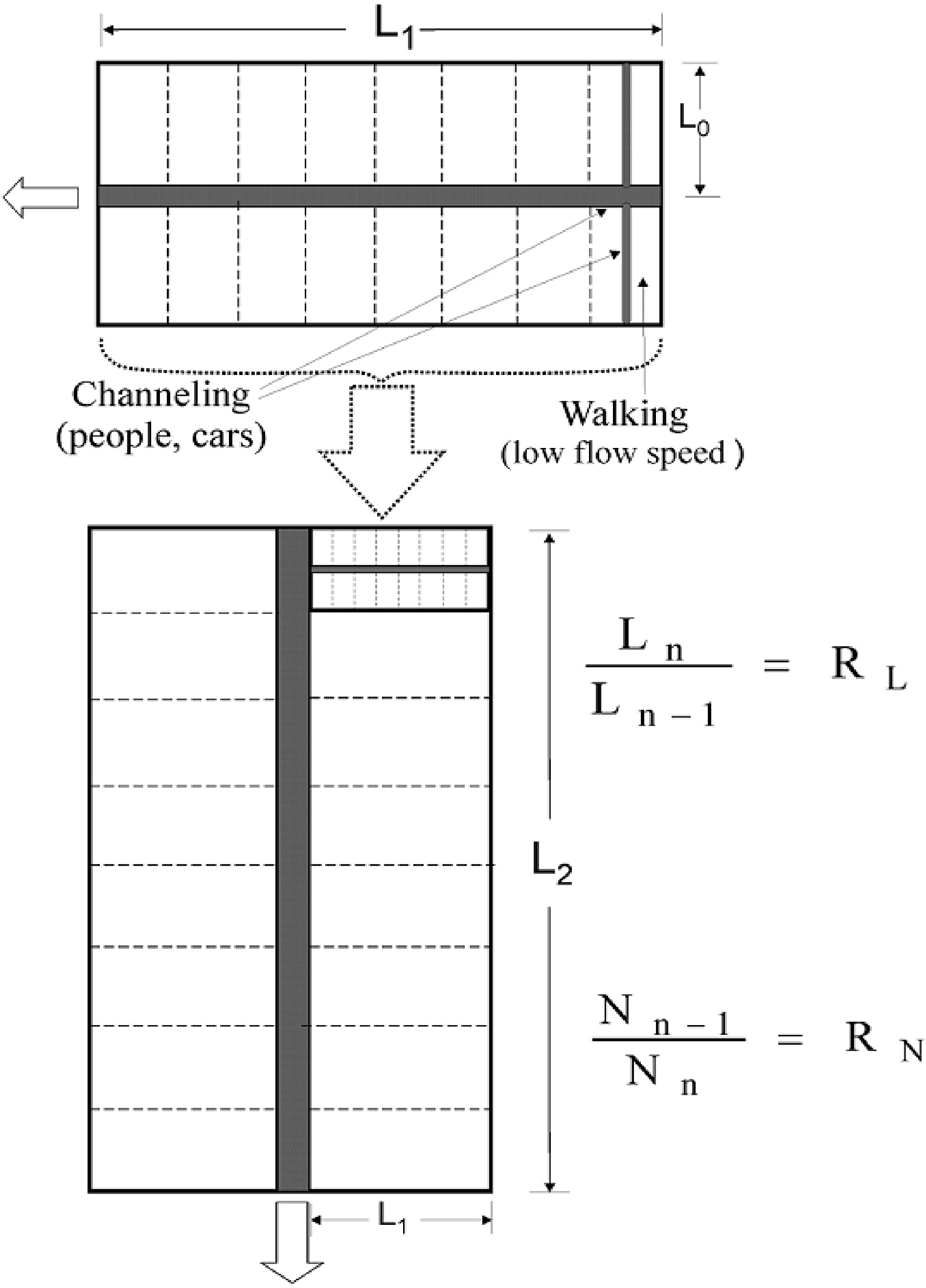

Fig. 7 Hierarchy of streams_in a city network. People living in the area of the smallest construct (top) walk "diffusively" before reaching the first channel where the flow becomes "organized". Then, flows proceed to a larger channel (street) that is tributary of the next order channel (bottom). Known scaling laws (constant ratio between consecutive channel lengths and consecutive numbers of channels) emerge from flow access optimization (Reis, 2008).

$$N(L_n) = (R_L^{-mn} R_N^{\ n})\, N(L_0) / R_N^{\ n} \tag{17}$$

Then, by comparing with eq. (15) one obtains the fractal dimension as:

$$m = \frac{\log R_N}{\log R_L} \sim 2 \tag{18}$$

which indicates that the fractal dimension must approach 2 for a city that developed its street network under the purpose of optimizing flows of people and goods (Reis, 2008). Of course many other factors do influence city development. However, if the purpose of making city flows easier and easier is the leading one, then we do expect that fractal dimension gets closer to 2.

Batty and Longley (1994) have determined the fractal dimension of cities by using maps from different years. They found values typically between 1.4 and 1.9. London's fractal dimension in 1962 was 1.77, Berlin's in 1945 was 1.69, and Pittsburgh's in 1990 was 1.78. Dimensions closer to 2 stand for denser cities.

Shen (2002), carried out a study on the fractal dimension of the major 20 US cities and found that the fractal dimension, m, varied in between 1.3 for Omaha (population – 0.86 million) and 1.7 for New York City (population – 16.4 million). In the same study it is also shown that in the period 1792–1992 the fractal dimension of Baltimore has increased from 0.7 to 1.7, which indicates that the city network has been optimized in time.

Chen and Zhou (2006) found that the fractal dimension of some German cities range from 1.5 (Frankfurt) to 1.8 (Stuttgart).

A systematic study on cities fractal dimension would be needed to fully confirm that cities street networks develop as predicted by the Constructal Law. However, the few results available all point to 2 as the limit of the fractal dimension of a city that would ideally developed in time under the purpose of better and better internal flow access.

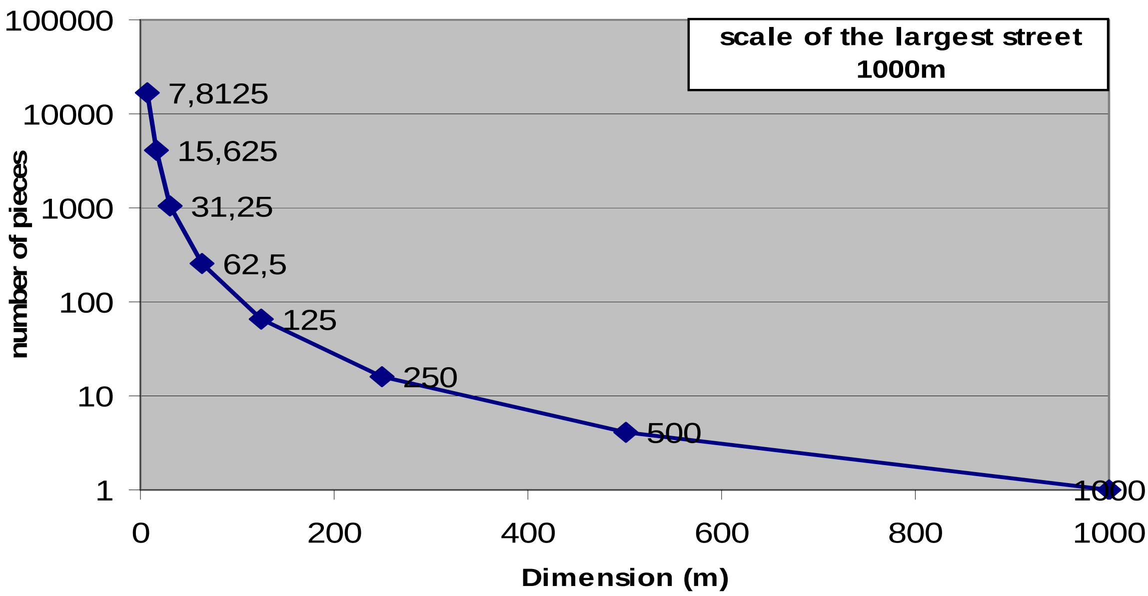

Fig. 8 . Distribution of the number of streets in a city in which the scale of the largest street is 1000m.

3.4 City street number distribution

The eq. 16 enables us to anticipate the distribution of the number of streets in a city according to the respective dimension. For example, Fig. 8 shows the distribution of the number of streets according to the respective dimension is a city whose largest street is 1000.

As a general remark we can say that cities optimize internal flows in time regarding the existing constraints, as predicted by the constructal law. This move toward better flow access is geometrically measured by the fractal dimension that approaches 2 as the limit defining optimality. City scaling laws start being used for guiding city policies regarding traffic regulation.

4. EXAMPLES FROM HISTORY

City organization has changed in time according to social organization and also to external constraints (wars, trade, etc.), and its marks have been preserved in the remains, especially in the architecture, of the ancient cities. We will discuss two different schemes of planning city space as a flow structure.

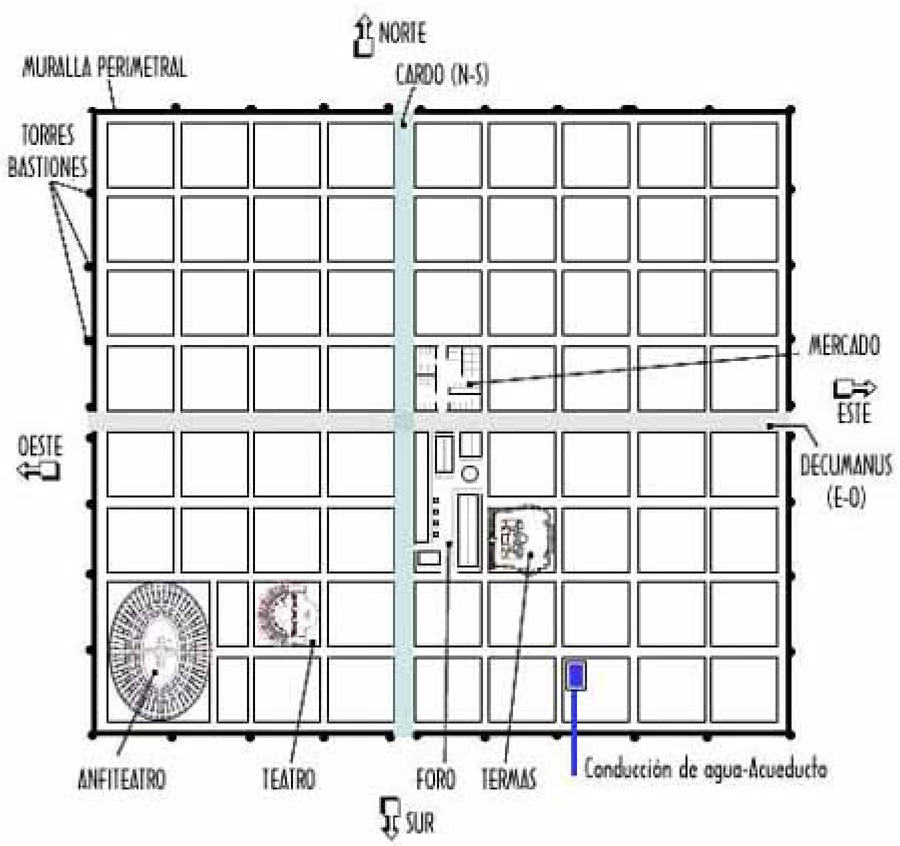

Fig. 9 Plan of a Roman city. The two main streets (via decumanus and cardo) cross at the center providing excellent drainage smaller street flows and flow distribution onto inside quarters. The external wall was present at the end of the Roman Empire due to the barbarian invasions.

The fist case is that of organization of Roman cities (Fig. 9). In general, these cities were built on open spaces and spread over relatively large areas. Cities were not much constrained by city walls that came later when the Roman Empire was under attack by the barbarians. The plan of the city usually followed a design in which two principal streets (*via*) cross at the middle of the city. These broad *via* received "flow" from tributaries on both sides (Fig.9). This "drainage network" with multiple mouths performed very well and, surely was efficient.

With river basins, the rule of quadrupling the number of streams from one scale to the next lower scale proved to promote the best performance (Reis, 2006a; Bejan, 2007). We can detect in the ruins of some

Fig. 10 Ruins of the Roman city of Timgade in now Algeria (photo by A. Crosnier). Note the street network designed for near optimal flow access, very close to optimized constructal design.

cities that Roman city planners had the intuition of the designs that promoted better efficiency with respect to city flows. Many of these designs approach the optimised constructal design of Fig. 12. Actually, cities in the vast territory of the Roman Empire, relied on the military power of the mobile legions for defence against invasions and, usually were not much constrained by external walls. Hence, city planners had to deal mainly with the efficiency of the city network regarding flows of goods and people (merchants, horses and carriages, military personnel, etc.).

Differently from the Roman cities, the medieval ones had to face constant wars under the feudal regime and later. Defence was a major concern and therefore, almost all medieval cities developed over a small area surrounded by towering walls. Movements to the outside were usually restricted to few gates that gave controlled access to and from the outside, hence people movement was restricted to a small inside area with the market at the centre. This point to area flow and vice-versa developed special flow structures, accordingly. Fig. 11a represents the plan of a medieval city, while Fig. 11b represents the medieval city of Bologna. The flow structure developed radially, and we may speculate if such a network is a result of structure optimization in time?

Actually, the flow problem is that of optimizing point to area flow access, especially for those that lived in the periphery (circumference). Lorente et al (2002) have addressed the similar problem of supplying water to users located along the edge of a circular area. The optimal flow structure, i.e. that network that supplies water without minimum resistance under the circumstances of scarcity of conduits is represented in Fig. 11b. As said before, this problem is analogous to that of people that have to move between the centre and the periphery (and back) of a medieval city (usually circular in shape), facing the constraint of scarcity of free space for the movement. The flow designs of Fig. 11, represent almost the same flow pattern, with a so amazing similarity, that we are led to the conclusion that also medieval cities have optimized their internal street network in time.

These two examples picked from History illustrate of how in the field of social organization, namely in city organization, the "fossil" flow structures as the ancient street networks are may be understood based on principle. These examples add to many other is various fields in which the constructal law proved to be a universal principle (see Reis 2006b).

Many cities yet preserve traces of ancient flow structures. In Fig. 12 , representing downtown Évora, which is a Portuguese city considered as Worl Heritage by Unesco, we can observe the central nucleus corresponding to the Roman city (though the design is already much altered) surrounded by the inner walls medieval city that spreads radially, and finally the modern part of the city. The modern part is little constrained, therefore exhibits a street network that provides easier flow access.

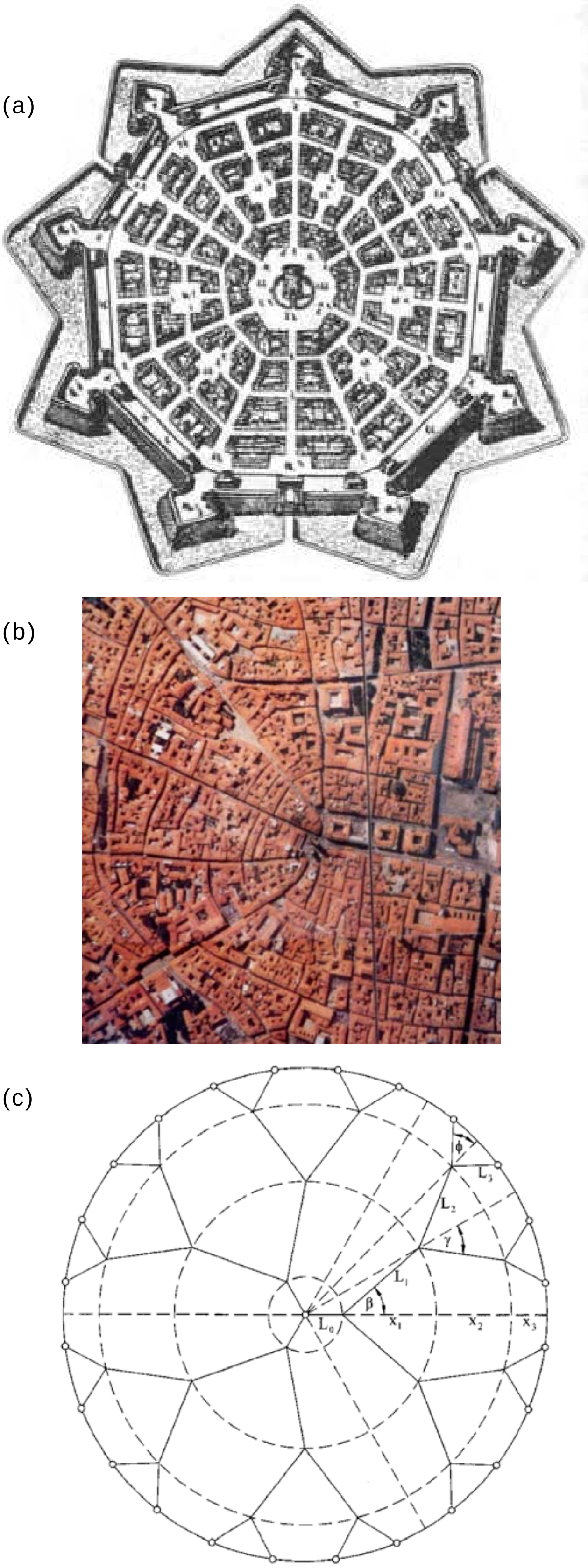

Fig. 11 (a) Plan of a medieval city; (b) Medieval Bologna (Italy).; (c) Constructal design for optimal flow access between the centre of the circle and points on the periphery (Lorente et al, 2002).

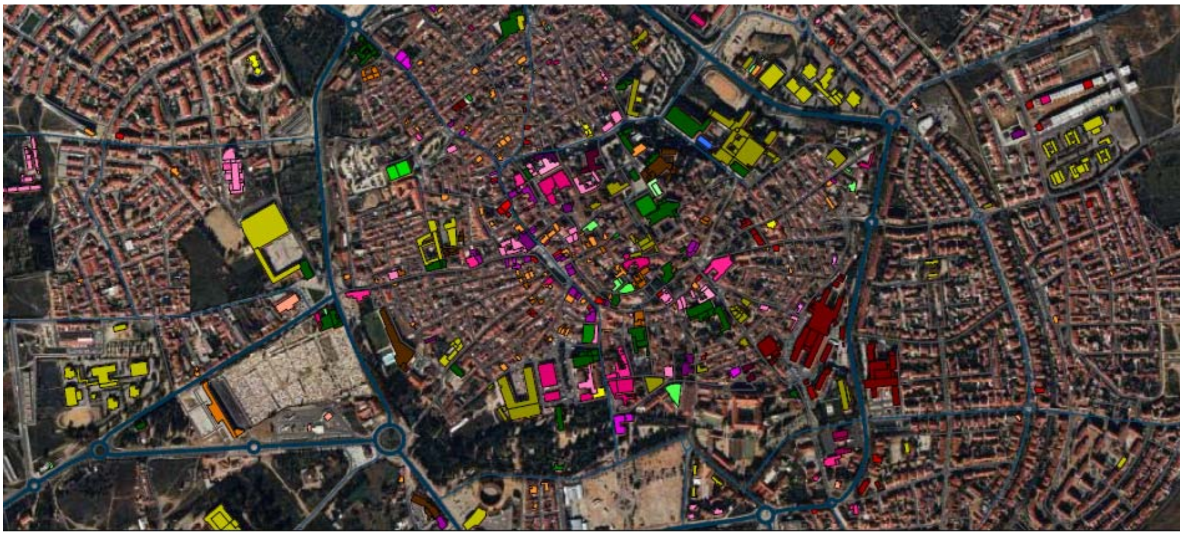

Fig. 12. The historical centre of Évora (Portugal). The nucleus corresponds to the area of the Roman city. The radial flow structure of the medieval city develops in between the nucleus and the modern part of the city.

5. THE CONSTRUCTAL CITY

Modern cities are systems that morph under multiple factor and constraints. Therefore, no city is planned based on a unique purpose. Multiple purposes, beliefs and constraints converge while planning modern cities. However, it may be useful to define the concept of "constructal city", especially if one of key purpose is to design a city network that performs optimally, i.e. with the lowest global resistance to flows of people and goods.

Hence, we may define "constructal city" as that with the street network that follow the constructal rules stated in Eqs. 14 and 15. In such a city each street receives traffic from for four lower-order tributary streets, two from each side (the quadrupling rule). Width and length of each street is defined according eq. (11). Flows of people start when individuals walking from their homes (neighbours) gather in the first little street, and proceed by walking or by using means of transportation of successively higher speed, until they reach the boundary of the respective destination areas where the flow scheme is reversed. The flow network of the "constructal city" is represented in Fig.12. We can identify in the constructal network many features of the ancient Roman cities. Either intuitively or even analytically, the constructal optimization rules were subjacent in many features of the past architectures.

5.1 Area-to-point flows and evacuation plans

The constructal law may also help in designing a simple plan for evacuation people from disaster areas. The purpose is to design the best evacuation path that every individual must follow in case of need to escape from a threatened area. Because the constructal flow system is designed on the purpose of providing the easiest global access it is also suited for draining people from an area to a collecting point in the minimum time.

The simple, and unique rule to follow is that "everyone must take always the widest street in the constructal city". This rule not only ensures optimum distribution of the flow of people but also that the flow will develop progressively with increasing speed. Hence, constructal networks would make a city safer in case of threat. This same network would be that might provide better access of protection agents (firemen, police, medical teams, etc.) from an area to the point of disaster.

At a smaller scale, the same constructal rules may be applied to public buildings or places frequented by a great number of people with the purpose of increasing safety levels.

In resume, constructal networks that are based on principle (constructal law) law will provide the best access in emergencies and deserve to be considered in security planning.

6. CONCLUSIONS

Cities are complex open systems with a complex vascular system (street networks) in which people and goods flow. In a certain sense, cities perform as living systems with their own "metabolism". As with animals, the power dissipated in cities scales with the ¾ exponent of city "mass", following the known allometric law. Taking advantage of such comparison some authors propose that the allometric law that states that the heart beat rate of animals scales with the ¼ power of body mass, might be used to define the changing frequency of traffic lights in relation with city "mass".

Despite the few examples were considered in this study, we believe that city networks evolve in time as the result of the continuous search for better flow configuration, therefore being a manifestation of the constructal law.

Analogy was established between the scaling laws of river basins and city street networks. It was shown that a law that is similar to that of channel flow governs city flows. This fact provided the basis for applying the constructal relations derived for river basins to city street configuration. It was found that self-similarity appears at the various scales while the fractal dimension must be 2, ideally.

The results seem to corroborate that well developed cities tend to approach fractal dimension 2 as anticipated by the constructal law. More, as cities develop in time and become more and more complex the fractal dimension tends to increase.

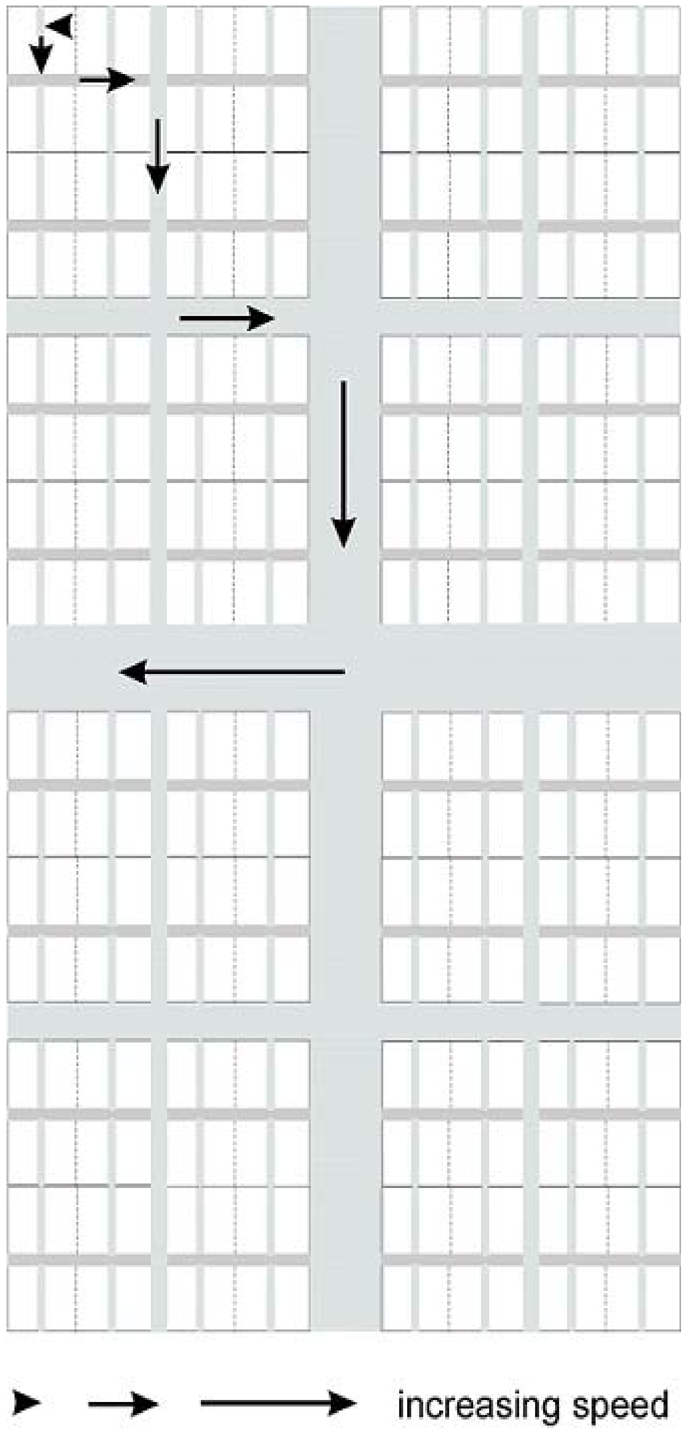

Fig.12 . Constructal city network and design of the flow path for evacuating people from threatened area to rescue point.

Examples of street networks of the cities of Roman Empire, and of medieval cities have been analysed in the light of the constructal law. We noted that all such networks represent the result of the struggle for easier flow access in very different constraints.

The concept of "Constructal City" was proposed as a paradigm for the easiest flow access. It was also shown that this concept might help in the design of evacuating plans of threatened areas.

These results add to many others that confirm that wherever something flows, flow architectures emerge, which can be understood in the light of constructal Law. Transportation networks where goods and people flow have been developed in time with the purpose of maximum access or best performance in economics and for facilitating all human activities. Similarly, internal flow structures where energy, matter and information flow are at the heart of engineered systems. Everything that flowed and lived to this day to "survive" is in an optimal balance with the flows that surround it and sustain it. This balancing act — the optimal distribution of imperfection — generates the very design of the process, power plant, city, geography and economics.

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