Morphological Modeling of the City and Its Transportation System: A Preliminary Investigation

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The morphological study of a growing entity, such as a city, deals with its structure and form. In biological sciences morphological analysis is essential for understanding the functions of the component parts of a growing system. Likewise, for city planners there is a need to really understand how a city grows, develops, and evolves. Urban growth components have been identified as objects of a system, where the system is defined as a set of objects together with relationships among these objects. A morphological model of a city therefore attempts to relate urban growth or decay to the urban infrastructure, such as its transportation and other life-supporting systems. This paper serves as an introduction to the morphological modeling of the city in general and the transportation system in particular. Since professionals of many disciplines are involved in city planning and design, it is expected that the morphological modeling of city systems also will involve knowledge distilled from several disciplines. Research findings in the areas of automaton, control, and stochastic theories could be integrated advantageously for use in such modeling through interdisciplinary research involving biologists, control systems engineers, city planners, system analysts, and transportation engineers. In this paper an explanation is presented of the morphology of city systems in terms of their growth and decay patterns and the basics of control theory, and, finally, a brief introduction is given to the biometrical modeling of the city. Several real-world applications of simple morphological and allometric methods applied to transportation systems planning are described. The need for a coordinated transfer of knowledge initially developed in systems control to urban system design is discussed. It is expected that such research will greatly benefit professionals involved in urban systems design and management, since morphological modeling of city systems will put the design components of the city in a new perspective. Several important and valid reasons are given that illustrate the superiority of morphological modeling over conventional analytical modeling as currently practiced.

One of the delights of science is the discovery and rediscovery of patterns of order in nature. These patterns are awesome not just for their beauty but because they suggest an order underlying their growth (and decay). This basic pattern-forming process indicates that certain proportions and limits occur over and over again in all forms of nature. Can the harmony that is apparent in natural forms be transplanted to man-made forms, such as the metropolis? With advancements in land use and communication theories coupled with even more spectacular strides made in biometrics and control theory, an interdisciplinary inquiry deserves critical investigation.

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The purpose of this paper is to serve as an introduction to the morphological modeling of the city in general and the transportation system in particular. Morphology is defined as the science of structure and form of a growing entity. A morphological modeling of the city, therefore, attempts to relate urban growth to the urban infrastructure, such as water distribution systems, sewage and waste water disposal systems, land use activity systems, power transmission systems, electronic communication systems, emergency management systems, surface (road and rail) transportation systems, and so on.

Over the years city planners have felt a need to really understand how a city grows, develops, and evolves (*1*). Because it is known that the development of one growth component is related in some way to that of the other components, the need to establish these relationships is logical. For instance, the land use pattern of a city does not develop independently of its transport facilities; on the contrary, it forms a closed-loop system (*1*, *2*). Indeed, urban growth components have long since been identified as "objects" of a system where the "system" is "a set of objects together with relationships between the objects" (*2*, *3*).

In biology morphological analysis deals with functions of component parts of a growing system. Biometrical modeling deals with the optimality of the performance of component parts under various conditions. For urban systems, however, no such modeling exists to date, although some analogies between the characteristics of urban components and those of biological components have been roughly drawn. Most urban systems models in use today are of the analytical type. It has been pointed out that the parameters of growth relationships of urban components must be interpreted differently from abstract biology, because unlike the typical biological systems where the growth information is fixed and embedded in the genes, the corresponding growth information in urban systems is determined by numerous decisions made by the policy makers over time (*4*).

Although a few researchers have demonstrated the use and application of morphological analysis in system planning and design (*5*, *6*, *7*), there is still a great need to study the metabolism of urban growth and the metabolic performance of the morphological components of the city. It is also necessary to identify the potential impacts of urban components on each other and on the total growth of the city. Therefore, it can be concluded that without such knowledge and understanding, the exact diagnosis and prognosis of urban problems and their treatment are well nigh impossible. Analogous to medical science, it is the knowledge and understanding that the medical profession has acquired about biological systems that allow its members to scientifically diagnose and cure the diseases of their patients. It can therefore be hypothesized that a critical examination of the growth and decay components of the city will reveal valuable insights in diagnosing urban problems. A morphological modeling of the city hopefully will permit one to understand urban problems through new ideas in automaton, control, and stochastic theories.

A word should be said about the form of this paper. The problem is one of presenting a subject where virtually everything is related to everything else. The crucial ideas center around several topics, and, therefore, questions such as what to present and when and which juxtapositions and continuities to hold and which to break are all problematic. However, the many detours and digressions hopefully will interest both the serious travelers and the casual spectators. The sum and substance of this paper may be read as proposing a problem or question, not as supplying a final answer; all it does is to lay the groundwork for further investigation and dialogue.

DEFINITIONS

Some of the basic concepts used in this paper are borrowed from the biological sciences and are defined briefly here.

Feedback Systems

Control systems that utilize feedback are called feedback systems. They are composite systems with at least two components: (a) a controlled system that is desired to execute a specific activity through the manipulation of the inputs by an amount depending on the deviation of the system at each time t from its desired position at that time and (b) a controlling system that computes the deviation of the controlled system from its desired behavior and then provides appropriate inputs to the controlled system by receiving a signal input from the environment and from the controlled system as a feedback.

Adaptive Systems

Systems that exhibit adaptive behavior are called adaptive systems. These systems can modify their activity, if necessary, to bring such activity to a preferred (or optimal) state with respect to particular environmental situations. Input-output error-actuated devices are good examples of these systems. Biological organisms demonstrate many different kinds of adaptive behavior. Understanding the adaptive behavior of natural systems is very important to biologists and psychologists. Likewise, the concepts are highly useful to the applied scientists and engineers who would like to incorporate biological adaptive systems as prototypes for man-made systems.

Biological Systems

A biological system has an inside and an outside. It possesses physically obvious compartments or organs and tissues that are composed of microscopic cells and relatively homogeneous entities called organelles. As opposed to a closed system, a biological system, like all other physical systems, is truly an open system. An open system is affected by its environment, whereas a closed system is isolated from its environment. A biological system also is a dynamic system since it shows a delayed response (i.e., its response to an output variable is not instantaneous but delayed because of the time taken for the input's effects to be transmitted to the system output). Feedback is one of the most important phenomena occurring in dynamic biological systems. The feedback mechanism may be illustrated by an example of thermoregulation. When the temperature information is fed back from the skin via the nervous system, the thermoregulatory center initiates action to regulate temperature at its desired level. If the information fed back indicates that the skin temperature is too low, signals are transmitted by the thermoregulatory system to the muscles to increase oxidation and, hence, augment the heat supply to the body. The reverse happens if the skin temperature is too high (*8*).

Morphology

As pointed out earlier, morphology is the science used to study the form and structure of a system and the functions of the components. In other words, a system can be defined uniquely by its morphology. A morphological study or analysis is, therefore, essential in understanding the behavior and vital characteristics of any system. Biologists are constantly using morphology in studying biological systems. Although the term rarely is used in general systems theory, systems analysts can in many ways be regarded as morphologists. Zwicky (*9, 10*) defined the exploratory techniques of systems planning and design as morphological methods. The method consists of describing the parameters and the fundamental aspects of a system process that is already known. The constituent elements of the process can be seen as a set of elements where each element may have several alternatives—that is, there are alternative morphologies (each made up of different elements) for the process as a whole. These alternative morphologies are described fully by the lattice of combinations of all alternatives for each element of the set with all other alternative elements in the set (*6*). The word "analysis" is not entirely descriptive of the technique's usefulness, for it can be employed both in forecasting future changes in forms or structures and as a normative device for pointing to possible future innovations in such forms (*9, 11*).

Allometry

Allometry defines the relationships between the form functionals of a system. Allometric relations (or at least correlations) between various pairs of different kinds of measurements yield insights into the underlying rationale of the objects under study and ultimately reveal how and why the objects behave the way they do. Rosen (*12*) points out that most of the important examples on allometry are drawn from growing systems. In growing systems the values assumed by a specific form functional (x) become an explicit function of real time t. This is so because the form F of the system is itself changing in real time: $F = F(t)$, and so $x(F) = x[F(t)] = x(t)$. Given two form functionals $x(t)$, $y(t)$ defined on growing systems, it is possible to eliminate time between them and to obtain a relation involving x, y alone. The most familiar growth law satisfied by a biological form functional $x(t)$ is that its increase is proportional to its magnitude at any instant. Therefore,

$$x(t) = kx$$

where k is a constant. This equation, characteristic of many biological systems, leads to

$$x(t) = x_0e^{kt}$$

where x_0 is the value of the form functional x at some initial time t_0. Systems obeying this equation are said to be growing exponentially. Now, for two form functionals x, y of a system with exponential growth, we have

$$x = x_0e^{k_1t}$$

$$y = y_0e^{k_2t}$$

which leads to

$$y = y_0e^{k_2t} = \frac{y_0}{x_0^{k_2/k_1}} (x_0e^{k_1t})^{k_2/k_1} = \alpha x^{\beta}$$

In other words, at least for growing systems, whenever any two form functionals of the system are growing exponentially, they are necessarily related by an allometric law. However, it should be noted that exponential growth rates are not the only ones yielding allometric laws (*12*). The allometric constants α, β (known as "structural constants" of the system) are, respectively, a ratio of initial values and the ratio of a pair of rate constants. Since the ratio of any pair of rate constants is always independent of time, the allometric formulation of the rate of growth equations can substitute for t a particular form functional as a kind of "physiological time" (i.e., the rate of growth of a form functional is no longer to be measured with regard to absolute time t but rather with respect to another form functional).

CITY SYSTEMS AND THE SYSTEM APPROACH IN PLANNING

The idea of systems stemmed originally from the biological sciences, and the early development of systems thinking was associated with the biologist Ludwig von Bertalanffy (*13*). In his *General System Theory* Bertalanffy viewed systems science as the unity of the conception of the world whose general principles are seen everywhere in inanimate things, organisms, and mental and social processes. The mathematical definitions of a general system are best given as follows (*14*):

- A set of implicitly defined formal objects,
- A set of elementary transformations T,
- A set of rules P for forming sequences T, and
- A set of statements indicating initial forms of the formal objects for use in generating new forms of the objects.

It will be useful at this point to examine the various kinds of systems as defined by systems philosophers:

- Natural or concrete systems—a nonrandom accumulation of matter-energy, in a region of physical space-time, that is nonrandomly organized into coacting interrelated subsystems or components (*15*). Laszlo (*16*) states that the naturalsystems (e.g., atoms, molecules, crystals, cells, viruses, organisms, ecologies, societies) are characterized by the measurable nonrandom regularity of the coactions of their components, generating conceptual invariances (i.e., different equations stating functional relationships between variables).
- Cognitive systems—a system constituted by mind-events, including perceptions, sensations, feelings, volitions, dispositions, thoughts, memories, and imagination—that is, anything present in the mind (*16*).

Chadwick (*6*) shows how a system can be characterized along with several subsystems as an input-output process through which there is a flow—information, energy, or matter. He points out that the human body is a commonly observable system; the relationship of man to his setting is an ecosystem—a community and its habitat, a group of organisms, and the soil, water, climate, and other physical features of the environment. According to Dice (*17*), such ecosystems can be of any size, from a drop of pond water to the whole earth and all its plants, animals, and human inhabitants, but both are systems in process, exchanging matter and energy continually between community and habitat.

The evolution of systems thinking has encouraged researchers to apply this approach to the modeling of human decision making in a sociophysical environment. Sociologists have applied these models to study problems in sociology and other social sciences that have been dealt with traditionally by philosophers. They have stressed that both the conception of the structure and the dynamic process of complex sociocultural systems require a better understanding of the microprocesses underlying the macrolevel. Ashby (*18*) warns that a normal analysis of a system will not be adequate to understand the system because a normal analysis process gives us only a vast number of separate parts or items of information, the results of whose interactions no one can predict.

The systems approach still is used widely in urban studies and urban planning. Chadwick (*6*) views planning itself as a conceptual system that starts with two directions of enquiry: the recognition and description of the system and the formulation of criteria for its testing, which advantageously proceed side by side. He notes that planning deals with very large systems that are, in cybernetic terms, very complex, have large variety, and can at best be specified only incompletely. According to him, planning should be seen as dealing with stochastic processes to specify the system statistically. The real world, he continues, is a complex system of both natural and man-made things that can be discerned to have a morphology with a characteristic and complex endogenous behavior undergoing irreversible change through the passing of time. Mesarovic (*19*) considers the city a complex system capable of counterintuitive responses, and it can be properly understood and controlled only if the interactions between four basic urban factors—the individual, the groups of people living or working together, the natural environment, and the man-made or technological environment—are accounted for properly. Alfeld and Meadows (*20*) point out that almost all of the urban programs initiated in the 1970s for raising the quality of urban life in American cities were failures because planners were looking at city problems on an individual component basis. These authors emphasize the need for a new theory to deal effectively with urban behavior; this theory must embrace a conceptual understanding of the city as a whole through various interrelated activities or functions. Doxiadis (*21*) views the crisis in cities through a systematic study of city growth. He explains this as follows:

- The city is a system of people living together, pooling their energies, and developing a community with a common economy that is growing out of balance in certain areas. People and the energy produced by them grew in the past at the same rate with the resultant economic growth, thus indicating a balance in the city system among people, energy, economy, and physical formation. The system components, however, have developed an imbalance during the last hundred years because of the differing rates of growth of population, energy, and economy. The commercial form of energy that helped people go far out of the cities has resulted in a system that cannot be supported properly in economic terms. This situation has, in effect, afflicted the citizens for the most part and, to a greater extent, the weakest economic groups of society.
- The city, like any other growing system, develops an increasing degree of complexity that is always served in nature or in society by corresponding physical and institutional structures. These structures do not correspond to the complexity of today's city systems as effectively as they did in the past.

Chadwick (*6*) gives a general classification of systems problems and concludes that the problems exhibited in the field of town and regional planning fall into three broad classes that can be stated in the form of the following questions:

- The analysis problem—the system exists in fact and its structure is or can be known; how will the system behave on the basis of a knowledge of its structure?
- The black box situation—the system exists but nothing is known about it, and its structure cannot be determined by direct means; how can one ascertain the behavior of the system and, if possible, its structure?

All of the above discussions on systems approach lead to one conclusion: the city systems, apparently perfect for the application of systems theory, should be adequately and completely defined and advantageously modeled so that the existing developments in systems concepts can be utilized effectively.

CITY FORM

That the city is characterized by form is an established fact; the form is one of impressive variety and social expression. From a physical standpoint, urban form exhibits huge variation—from concentric cities to linear cities. However, urban form is not merely a matter of descriptive geometry.

The idea of form essentially has two aspects: morphological and conceptual. Morphologically, the idea of form refers to its visible aspects, in terms of the arrangements of parts and delimited entities. On the other hand, conceptually, the idea of form refers to its componential and inferential aspects, in terms of appearance, of imputation, and of differentiation of parts. The significance of these two aspects is illustrated in Table 1.

Form follows function and is fitted to function; function also is fitted to form. Variation of form may (as in urban form) be seen as an adjustment to the level of function. For example, in an urban area one might make adjustments of first-order functions, such as defense and security, and these might induce adjustments in second-order functions, such as transportation, business, and industry, which, in turn, might then force adjustments in third-order functions, such as the economy, and these may cause adjustments to be made in fourth-order functions, such as individual life-styles, access to the social structure, and mobility. And so the list goes on.

Urban form can be regarded as an agency of input-output process, as an instrument or system of commerce and industry, as a complex pattern of paths and locations, or as social space. In all these examples of the idea of form, there is an unmistakable linkage between form as product and form as process—in other words, between form and form giving (*22*).

MORPHOLOGICAL ANALOGY OF THE CITY

Biologists and paleontologists consistently have investigated the growth pattern of entities in terms of the relationships among system components and between the components and the whole. They have been successful in establishing the state of equifinality (i.e., a growth status in which the components of entities with growth characteristics grow in time at an established rate). Systems having growth phenomena, such as biological organisms, have been studied morphologically for a long time. The relationships between the components have been reported to approximate allometric relations of the form

$$m = aM^b \quad (a, b > 0)$$

where

m = measurement of the system component,
M = measurement of the whole system, and
a and b = constant characteristics of the system's components.

The urban system has been considered as a system of growth phenomena consisting of several components which themselves behave as growing systems. Bertalanffy and Naroll (*23*) demonstrate that the relative growth of urban and rural populations in nations and regions can be usefully compared by fitting power function equations to the observed growth of these components. Stewert (*24*) discovered a regular allometric relationship between the urban fraction of the population of the United States and its total population over 15 decades of growth. The allometric relations are based on the principle that during the growth of a system, some basic measurements of system components remain proportional to constant powers of measurements of the whole system. Thus, an allometric formula can be used in the measurement of relative growth in which a given dimension of a part of a system is compared to the corresponding dimension of another part of the same system or of the whole. This makes allometric analysis very useful for designating the differences in proportions correlated with changes over time in absolute magnitude of the total system or of the specific components under consid-

TABLE 1 IDEA OF FORM AND URBAN FORM GIVING (*22*)

Urban Form	Urban Form Giving
Morphological	
Arrangement of parts	Market determination of land use patterns and building types;
	Topographical/geographic determination of land use patterns and building types;
	Ecological distribution patterns and processes;
Boundaried entity	System determination of urban functions, location, articulation, pattern;
	System models in planning and management development of cities;
Realization of essence	Urban physical/social structures as developmental functions of interests, needs, goals of human community;
	Utopian, ideal, designed cities as realization of human values inherent in the human community;
Conceptual	
Appearance	Physical structures of city = f (urban social structures);
	Social structures of city = f (urban physical structures);
Imputation	The symbolic shrine/palace city of archaic/classical urbanisms;
	Urban forms as social/perceptual spaces;
	Urban social form as social constructions;
Differentiation	Types of cities in terms of dominant functions;
	Types of cities in terms of dominant culture/economy/polity;
	Types and functions of urban social structures.

eration. In studying growth phenomena, the constant a of the allometric equation is termed the initial growth index, while b is termed the equilibrium constant or, in absolute size comparisons, the limiting equilibrium constant.

Based on the concepts discussed above, we formulate some morphological analogies of city systems:

- Natural systems such as living organisms grow on the basis of their fixed morphology. The processes of nature are carried out in the best possible manner, described by allometric equations. Similarly, the components of the city also must grow in certain proportion to the whole system. The design for the city's form and structure should be planned so that its growth is optimal. In other words, the infrastructure systems of the city should be designed such that the total energy expenditure (e.g., movement from one place to another) is the minimum.
- The growth decisions for a living organism are made by its genes according to some fixed optimality criteria. For a city, planners and decision makers correspond to genes in a living system. They ought to follow certain rules to be developed from a morphological modeling of the city for the purpose of normative planning.

Therefore, it can be pointed out that a clear understanding of a biological growth process in terms of the genes and morphological components will be useful in developing the criteria for the appropriate growth of a city.

BIOMETRICAL MODELING OF THE CITY

In this section we try to describe the city systems in terms of the governing theories of biometry. It is important to investigate how mathematical modeling is accomplished for the biological system through the use of concepts and theories developed originally by engineers and applied scientists. The following is a brief account of the theories that we believe will be useful for modeling the city.

Theory of Abstract Dynamical Systems

The theory of abstract dynamical systems is obtained by turning around the theory of classical mechanics. By using the set of rules of classical mechanics that tell how each observable of a system may be expressed in terms of the state of the system at each instant of time as postulates, it is possible to specify a new class of state of the system that satisfies the postulates. According to the theory of input-output systems, any external force impressed on the system, in general, is called an input to the system, and any observable of the system that can be expressed as a continuous function of the coordinates is called an output of the system. Rosen (*12*) formulated the central problem in the theory of abstract dynamical system as follows: by manipulating the inputs to a dynamical system, can one force the system to produce a preassigned output? In other words, can an appropriate choice of input be made that will cause a system to assume a preassigned state?

Theory of Optimal Control

The inputs to a dynamical system generally are called controls. The application of external forces, or controls, to a mechanical system may greatly alter the set of states the system may assume. Rosen (*12*) states the central problem of control by using the following example: if a ballistic missile or space vehicle assumes a trajectory that differs from the one desired, is it possible by means of appropriate controls to force the vehicle back to the desired trajectory? Consequently, the question that derives from the theory of optimal control is this: how can the inputs to a system be chosen in such a manner that the transition to the preassigned state is made in the "best possible" way? For optimal control of a linear dynamic system, two things must be defined: (a) an admissible set of systems that will exhibit the behavior desired and (b) some kind of index of the activity, or cost functional in terms of the set of possible controls, which is to be minimized. Most of the applications of the theory of optimal control are concerned with bringing a dynamical system from some initial state to some desired final state at some terminal time.

Theory of Adaptive Systems

According to this theory, the state of a system at any instant is given by the values assumed at that instant by an appropriate set of "state variables," which in the case of dynamical systems are linear combinations of the outputs of the system. For an adaptive system there exists for each possible input a set of one or more preferred states or outputs. If the system is not initially in a preferred state, the system will act so as to alter its state until one of the preferred states is achieved. Rosen (*12*) indicates the problem in the theory of adaptive systems as follows: given a system, together with an input $f(t)$, an output $g(t)$, and a preferred response of the system with input $f(t)$ as $h(t) \neq g(t)$, how can the actual response be altered to achieve the preferred response? The ways in which this can be done are two: (a) the desired response $h(t)$ can be achieved by modifying the input $f(t)$ until it becomes identical with an input $k(t)$ known to produce $h(t)$ and then presenting this modified input to the system, and (b) the desired response $h(t)$ can be achieved by causing an alteration to the transfer function so that it takes the form of a function known to belong to a system that produces $h(t)$ from input $f(t)$. Possibility (a) appears to be the characteristic of many applied feedback systems because of the simplicity in implementing it. Here, the input is modified by means of the feedback loop and converted to an error signal that tends the system toward the desired response. Possibility (b) is a rather more drastic one involving a change in transfer function of an input-output system. Adaptation in many biological systems and others of technological interest frequently is governed by possibility (b), which is also known as "feedback through parameters." This is the reason why biological processes often are nonlinear when considered from the viewpoint of systems theory. It is also interesting to note that naturally occurring adaptive systems often choose possibility (b) rather than possibility (a).

Theory of Finite Automata

The theory of finite automata is useful in modeling the simplest forms of behavior (*25*). An automaton is considered to be an object capable of receiving a finite number of signals, $s \in (s_1, s_2, \ldots, s_N)$, at every instant of time, $t = 1, 2, \ldots$, and changing its internal state in accordance with these signals. The automaton can carry out a finite number of actions, $f \in (f_1, f_2, \ldots, f_x)$. The choice of the action is determined by the internal states, $\phi \in (\phi_1, \phi_2, \ldots, \phi_m)$; the number m is called the memory capacity of the automaton. It is assumed that the automaton is situated in a certain environment and that the actions of the automaton cause responses s of the medium C. These responses are, in turn, the input signals of the automaton. It uses them to decide its further actions. Tsetlin (*25*) formulates the behavior of people in a town as a problem that can be well described in terms of the theory of finite automata. In this problem, given a town with a population of N people and n regions with room for $b_1, b_2, \ldots, b_n$ persons and m factories whose demand for labor is $a_1, a_2, \ldots, a_m$ persons, it is assumed that $N = a_1 + \ldots + a_m = b_1 + \ldots + b_n$. The population distribution is given in the form of a matrix (x_{ij}), $1 \leq i \leq m$, $1 \leq j \leq n$, where x_{ij} is the number of persons living in the jth section and working in the ith factory. Therefore, $\Sigma_j x_{ij} = a_i$, $\Sigma_i x_{ij} = b_j$. The distribution of factories and sections is such that a person with an index (i, j) needs time t_{ij} to get to work. Now, if the town residents exchange living quarters to shorten their commuting time, how can one describe the dynamics of the population redistribution in the town as a result of address changes and describe the distribution that is reached in the limit? A determination of such a stable population distribution is important in forecasting traffic flows in a city that is in the planning state.

SOME APPLICATIONS

Examples of the use of simple morphological and allometric methods applied to transportation systems planning are given below.

Morphological Method Applied to New Town Design

Chadwick (*6*) has applied the morphological method as an exploratory technique in examining possible options and combinations in designing a new town (see Figure 1). An alarming number of possibilities results in $2 \times 3 \times 5 \times 4 \times 4 \times 5 \times 4 \times 3 \times 3 \times 3 \times 2 \times 2 \times 3 = 3{,}110{,}400$. Of course, the best way of reducing this incredible number is to eliminate those options that have internal inconsistencies; for example, a linear town cannot possibly have a triangular street network. In addition, such factors as the topography of the town site would further eliminate some of the options. Figure 1 illus-

Regional pattern	Dispersed	Concentrated			
Regional network	Grid	Radial	Linear		
Regional transport (mode)	Rail	Transit	Waterway	Motorway	Hovercraft
Overall town form	Dispersed	Linear	Concentrated	Stellar	
Town network	Radial/Concentric	Grid	Directional grid	Triangular grid	
Town transport (mode)	Road/Bus	Road/Car	Transit	Dial-a-bus	Tram
Employment location (basic)	Dispersed	Concentrated	Commuter i.e. Regional		
Employment location (service)	Dispersed	Concentrated	Commuter i.e. Regional		
Residential location	New employment	Near recreation	Near services		
Residential density	Low	Medium	High		
Service centre location	Hierarchical	Polynucleated			
Educational location	Local	Campus			
Recreational space pattern	Belt	Wedge	Dispersed		

FIGURE 1 Morphological method applied to a new town design.

trates the various factors and the choices available under each of these factors.

The concept of morphological analysis was perceived and applied by Zwicky as early as 1942. He advocated its use in the fields of discovery, invention, and research. In his own words (*9*):

> Morphological analysis and morphological planning and execution of large-scale projects have been conceived for the express purpose of properly appraising *all* of the facts (or scientifically speaking, the boundary conditions) needed for the biased deduction of the possible solutions to any given problem. Only after all of these solutions have been thoroughly evaluated do we select the one among them that best satisfies our requirements.

The merit of this approach lies in its extraordinary suggestive power that results from its systematic exploratory behavior. Because of this power, the whole class of discoveries and inventions in a given field are made possible not only systematically but also simultaneously.

Efficiency of Alternative Network Designs

Different geometric patterns of road network are associated with different relative accessibilities. Smeed and his associates were able to calculate the average distance traveled on the streets of a city by the shortest route and their calculations revealed that $d = 0.87A^{1/2}$, where d is the distance traveled in miles and A is the area covered by the city in square miles. Smeed also established allometric relationships between d and A on a variety of street patterns as shown in Figure 2, indicating the advantage or otherwise of adopting a particular configuration of streets (*26*).

Alternative Routing Systems

Holroyd studied a variety of differing routing systems for circular cities. Some use internal or external ring roads, whereas others rely on radial and grid pattern lattices. The efficiency of the networks is evaluated in Table 2 for internal trips. Figure 3 shows the networks and average distances traveled between random pairs of prints. This procedure allows one to determine the type of street configuration most suitable for adoption in a city. Table 2 shows the average length of trips and the street length for each configuration. Note that trip length ranges from 0.905 miles to 2.237 miles. The most efficient alternatives are the radial, internal ring, and rectangular, as shown in Figure 4 (*26*).

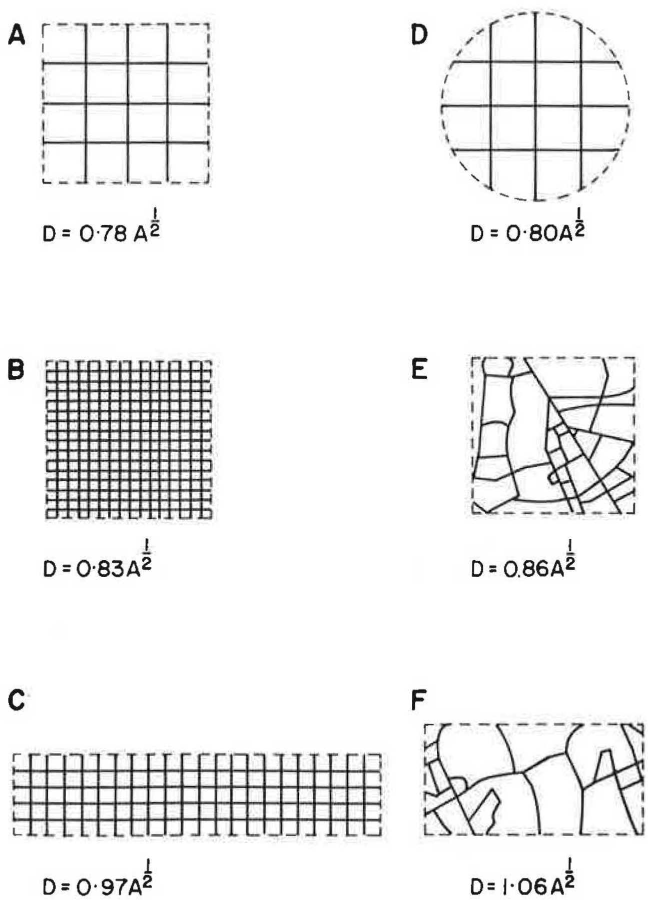

FIGURE 2 Efficiency of alternative city networks.

TABLE 2 AVERAGE LENGTH OF TRIPS IN A CIRCULAR CITY

CONFIGURATION	TRIP LENGTH (MILES)	STREET LENGTH (MILES)
1. DIRECT	0.905	∞
2. RADIAL	1.333	24
3. EXT. RING	2.237	30.28
4. INT. RING	1.445	27.14
5. RADIAL-ARC	1.104	42.84
6. RECTANGULAR	1.153	28
7. TRIANGULAR	0.998	43
8. HEXAGONAL	1.153	45

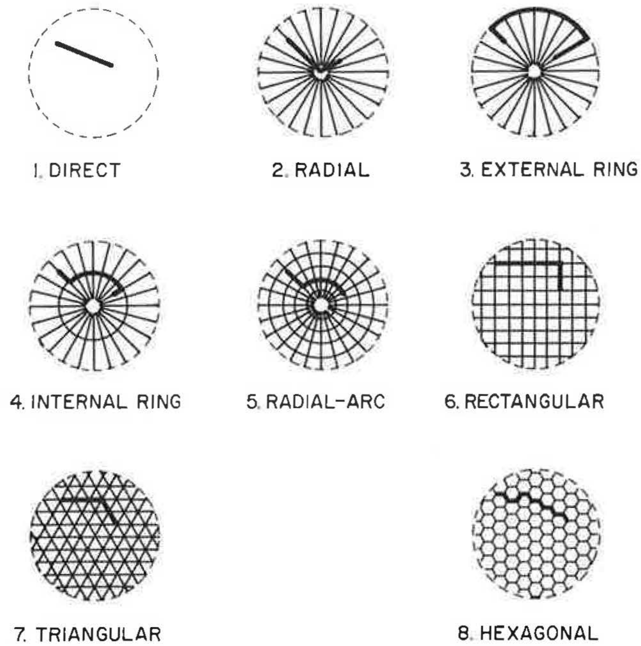

FIGURE 3 Alternative routing systems.

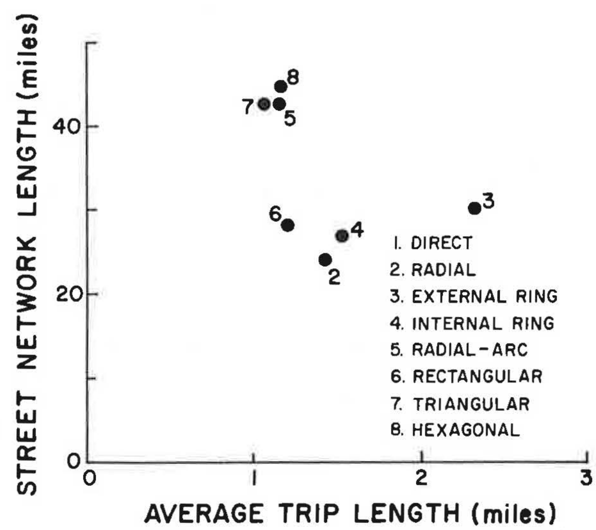

FIGURE 4 Average trip length versus street length.

Morphological Analysis of a Metropolitan Highway System

The benefits to be derived from morphological modeling of the city are versatile. Since professionals of many disciplines are involved in city planning and design, it is expected that the application of morphological modeling of city systems also will involve several disciplines. For the sake of illustration, let us consider the design of some components of an urban transportation system. City population can be considered as the most important measurement of the city as a whole entity (M); its component systems will have some measurements, m, that are to be determined for design purposes using the allometric relationship

$$m = aM^b \qquad (a, b > 0)$$

where a is the initial growth constant and b is the equilibrium constant of the growing systems under consideration. For example, the total number of trips made by the city population on an average day can be considered as the measurement, m, of the transportation component of the system. Using the statistical data with reference to M and m, an important relationship between these two variables can be derived where constants a and b can be calibrated. This relationship can be used for future design in estimating the expected number of total trips where the city population can be projected to a horizon year.

Now the total number of trips can be used as M for the transportation system (now a whole system itself), and components of the transportation system, say the length of roads in the city, can be considered for design. By denoting the total length of roads as m and using the morphological relationship between total number of trips per day and road lengths, one can continue to establish other system components, thus shooting for the proper balance in the system at any instant in time. This will enable the engineer to determine any deficiency or surplus in the provision of roads and to take actions accordingly. Since both deficiencies and surplus in a system are reasons for imbalance, the procedure will help to identify the sources of problems the city might face at some later time.

The results of these analyses will indicate patterns that may be considered as "norms" reflecting a collective societal logic in determining what is good for society. It is a proven fact, although not widely known, that there are many partial equilibria among an urban system's components, and each one of them is connected with an equilibrium norm. In the simple application given above, the following six questions are being raised:

1. What are the norms that are able to maintain the existing highway and mass transportation facilities within an urban area?
2. What structure (network) parameters can be identified that bring order (or disorder) to the existing highway and mass transportation system?
3. How do the equilibrium parameters and norms interact among and between themselves in providing a given level of service for transporting people?
4. What is the sensitivity of highway and mass transportation components to changes in the demand for transportation?
5. Can these sensitive components be sorted out and then used for attaining an optimum arrangement toward balancing the highway and mass transportation facilities?
6. Can land use arrangements coupled with sensitive components of transportation be incrementally or radically altered for optimizing traffic flow vis-à-vis harmonious land use patterns?

Balkus and Olsen (*4*) have applied a morphological analysis approach to a metropolitan highway system to establish an allometric relationship between M, the demand measured by miles driven per day per square mile of land area; L, the availability of facilities for meeting this travel demand measured by road miles per square mile; F, miles of driving surface measured in foot miles per square mile; and d, the vehicular trip end densities.

$$M = 36.09d^{0.8122} \qquad R^2 = 0.86$$

$$F = 0.3458d^{0.6081} \qquad R^2 = 0.94$$

$$L = 0.0319M^{0.5522} \qquad R^2 = 0.80$$

One can perform a sensitivity analysis from the above size comparisons because the exponents are the corresponding elasticities. Structural parameters can be discovered through such morphological analysis. Also, these three relationships can help one to visualize the regularities of the highway system's arrangement, and they also can help to serve as criteria in laying out a highway system in a new community or, possibly, correcting a system already existing.

NEED FOR RESEARCH

The discussions in the previous sections encourage one to believe that for a proper growth of the city system, an intelligent growth control system, if available, will be useful to the decision makers of the city. An intelligent control system is defined as an adaptive control system where the range of uncertainty to handle the system is substantially wide. The objective of intelligent control systems is to ensure an acceptable performance of the controller over a wide range of uncertainty. Three approaches that have the potential for intelligent control are as follows (*27*):

- Expert systems as adaptive elements in a control system,
- "Fuzzy" calculations as decision-producing elements in a control system, and
- "Neural networks" as compensation elements in a control system.

The first two approaches have been used extensively but narrowly in several areas of urban planning in the last decade with some success. The third approach using neural network has attracted researchers in control theory quite recently. A neural network has been defined as a system of interconnected elements modeled after the human brain. A network of "neuronlike" units operates on data all at once rather than step by step. One of the interests of researchers of neural networks is the investigation of the operation and structure of biological neural networks. Algorithmic work in neural networks has concentrated on computationally intensive areas of signal processing, such as adaptive pattern recognition, real-time speech recognition, and image interpretation. In systems and control, real-time identification and control of large flexible structures in aerospace is one such example of a computationally intensive area. Concepts developed in these areas might be useful in controlling and planning urban areas.

It is obvious that an integration of concepts and theories developed over the last few years is essential to provide decision makers of city systems a useful tool based on biological system morphology. The model may be able to apprehend the complexity of problems associated with the growth of city systems, thus serving the purpose of making appropriate policy decisions by the city planners. Since this approach of understanding city systems is innovative and promising, the following objectives may be undertaken in such research:

- Studying the decision making mechanisms relating to the "growth of the city system" in various types of cities (growing, stable, or decaying) across the nation;
- Analyzing the problems involved in decision making processes that currently exist in cities;
- Examining critically the decision making mechanism used by biological systems to maintain their growth (findings of research on neural networks might help in this investigation);
- Identifying important morphological components of the city (similar to the morphological elements of a biological system) and analyzing their functions in structuring the city; and

• Utilizing the research findings in developing a decision making model for intelligent control of the city by policy makers (this model will serve as a useful tool for city engineers and planners in analyzing alternative plans and in providing sufficient information to policy makers in adopting the optimum course of action in a given situation).

More specifically, in the preliminary stages of research the following tasks may be accomplished to develop the model:

1. Identify system parameters.
2. Determine a "minimal" set of physical variables to be used as state variables of the system model.
3. Determine or hypothesize the component models (i.e., the relationship among state variables).
4. "Connect" component models or define compartments to generate an overall model.
5. Specify the desired system responses (external and internal, measurable and inaccessible).
6. Specify admissible inputs (e.g., available resources and current policies).
7. Determine the "cost functional" (performance index, system objective) of the system. The notion of carrying capacity could be emphasized.

After the model is developed, a case study could be undertaken. This could include the following:

• Analysis of the system,
• Synthesis (optimality),
• Simulation, and
• Refining of models via aggregation of variables, compartments, and so on.

Finally, research could be performed to operationalize the model. This would include the following:

• Physical interpretation of results obtained from case studies,
• Implementation issues (feasibility and reality), and
• Comparative studies (i.e., advantages over other methodologies).

CONCLUSION

In conclusion, one might well ask the following. Why is morphological modeling superior to conventional analytical modeling and why does it lead planners in more productive directions? Eleven important and valid reasons answer this question:

1. Morphological modeling inherently is compatible with the systems approach, well known to planners, and provides a sound basis for the diagnosis and prognosis of urban problems.
2. Morphological modeling reveals valuable insights regarding the growth and decay of various components of the city, as well as the entire well being of the city.
3. It can be employed both in forecasting future changes and as a normative device in pointing to possible future changes and need for control.
4. Cities are a complex system of both natural and man-made components that can be discerned to have a morphology undergoing irreversible change through time. The myriad interactions between individuals, groups of individuals, and the natural and man-made environment can best be captured through morphological models.
5. Analytical models currently used in solving urban problems in the 1970s and 1980s have proved to be partial failures because they have examined individual components of the city system.
6. Natural systems grow on the basis of their fixed morphologies and can be described precisely by allometric equations. Similarly, the components of the city must grow preferably in certain fixed morphologies to the whole system. Hence the need for morphological and allometric analysis.
7. Morphological modeling has extraordinary suggestive powers that result from its systematic exploratory behavior.
8. Application of morphological analysis on a broad and realistic basis for policy-directed urban analysis harmonizes with the need for overall improvement of the quality of life.
9. The steps in such analysis are highly interrelated, sequential, straightforward, and direct.
10. Recognizing the importance of morphology and allometry, Dutton states the following (*28*):

> Allometric concepts and the analysis of relative growth may help to fill our current vacuum of ignorance concerning relevant norms of societal growth and change. As humanity takes conscious control of the planet which shaped the species, the analysis of relative growth can indicate what changes are possible, which are most likely, and to some degree, which may be desirable. By attending to changes in shape of our social organism, we may become more competent in shaping change.

11. Zwicky, who was responsible for introducing morphological analysis to the scientific community, writes the following in connection with morphology (*9*):

> Morphological analysis and morphological planning and execution of large-scale projects have been conceived for the express purpose of properly appraising *all* of the facts (or scientifically speaking, the boundary conditions) needed for the unbiased deduction of the possible solutions to any given problem. Only after all of these solutions have been thoroughly evaluated do we select the one among them that best satisfies our requirements.

The concept of morphological modeling of city systems is a relatively new and innovative idea in urban planning, design, and control. The similarity that city systems have to biological systems in their growth and decay commands the immediate attention of researchers in the areas of city systems planning, transportation, control theory, and biometry. Therefore, a coordinated research is essential to transfer knowledge already developed in systems control and microbiology to urban systems design and control. It is expected that such research will greatly benefit professionals involved in urban systems design and management because morphological modeling of city systems will put all of the design components of the city into one perspective.

An explanation is presented of city systems, the morphological analogy of the city in terms of growth and decay patterns and control theory, and, lastly, of biometrical modeling of the city. Still, there are much larger questions that remain unanswered, and these hopefully will be addressed when further research is carried out.

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