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Article

Editorial. Emergence: Developing a model of complex urban systems

Journal of Urban Management

Provided in Cooperation with:

Chinese Association of Urban Management (CAUM), Taipei

Suggested Citation: Lai, Shih-Kung (2023) : Editorial. Emergence: Developing a model of complex urban systems, Journal of Urban Management, ISSN 2226-5856, Elsevier, Amsterdam, Vol. 12, Iss. 2, pp. 89-95,
<https://doi.org/10.1016/j.jum.2023.03.002>

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<https://hdl.handle.net/10419/271494>

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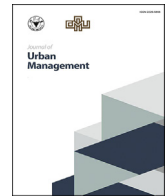
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Journal of Urban Management

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Editorial

Emergence: Developing a model of complex urban systems

1. Background

There has been a paradigm shift in modeling complex urban systems from an aggregate approach that views the systems as consisting of populations of homogeneous individuals to a disaggregate perspective that attempts to describe how individuals act and interact in a spatial setting (Batty, 2005). This has been accompanied by a paradigm shift in science in that the focus has changed from looking at a complex system in terms of its separate atomic components to attempting to understand how the system works. It is now viewed as being more effective to look at how individual components behave and interact as a whole, revealing the holistic characteristics of the system that emerge from such atomic behaviors (Waldrop, 1992). This editorial intends to address two interrelated questions at the crossroads of these two shifts: (1) how do complex urban systems work? and (2) how do exogenous/endogenous plans interact with these systems? Viewing the plans and the city as a loosely coupled whole, we intend to consider urban phenomena as a manifestation of emergence and develop a conceptual model to investigate what characterizes urban emergence.

Even within the disaggregate camp, there is a variety of modeling approaches to simulating complex spatial systems, such as cellular automata (CA) and agent-based modeling (Allen & Sanglier, 1981; Almeida et al., 2003; Batty et al., 1999; Batty & Jiang, 1999; Benenson, 1998; Benenson & Torrens, 2004; Berger, 2001; Besussi et al., 1998; Guan & Rowe, 2016; Liu & Phinn, 2003; McConnell, 2002; Miller et al., 2004; O'Sullivan, 2001; O'Sullivan & Haklay, 2000; Parker et al., 2003; Parunak et al., 1998; Ward et al., 2000). The idea of CA is derived originally from computer science, but the current CA approach to modeling complex spatial systems seems to deviate from what was originally proposed. We would argue that CA are not iconic models that mimic how a system behaves but abstract modeling languages, similar to mathematics, that serve as analytical tools for describing how systems work. In contrast, agent-based modeling ignores how intangible entities, such as decision situations and institutions, emerge and affect agents' behaviors by seemingly focusing on physical objects and debating the meanings of agents (Parker et al., 2003). A more realistic modeling approach would incorporate both tangible and intangible entities into a common simulation framework and simulate how they interact so that the holistic characteristics of complex spatial systems could be derived and investigated. Therefore, the methodological approach that is developed and used in this editorial includes both tangible and intangible entities in modeling complex urban systems. In particular, we intend to develop a conceptual urban model based on a general setting of emergence, namely, constrained generating procedures (CGPs) (Holland, 1998), that incorporates both CA and agent-based modeling into a common framework.

The theoretical framework that we intend to adopt in understanding how complex urban systems work is the spatial garbage-can model or SGCM (Lai, 2006) as translated into CGPs through network science (Watts & Strogatz, 1998), or SGCM/CGP/NW. We do not pretend that SGCM/CGP/NW is a complete, true description of how complex urban systems work, but we argue that it is rich enough to encompass most entities and their associated functions in urban areas. Based on the SGCM/CGP/NW framework, promising hypotheses and effective tools for deriving conclusive explanations for urban phenomena can be observed. Thus, strategies to make plans for urban development can be investigated.

2. The spatial garbage-can model

The SGCM was developed from the garbage-can model originally designed by Cohen et al. (1972) and extended by Lai (1998, 2003) to examine the effects of planning in an organizational context. The conception of the garbage-can model is shown in Fig. 1. In the simplified diagram, the inputs of the model are the sequences of problems, solutions, and choice opportunities, while the outputs are decisions. An organizational system composed of decision makers is facing incoming problems, solutions, and choice opportunities in time. As the three streams of elements flow into the system in an unpredictable, random way, decision makers, solutions, and problems

<https://doi.org/10.1016/j.jum.2023.03.002>

Available online 1 April 2023

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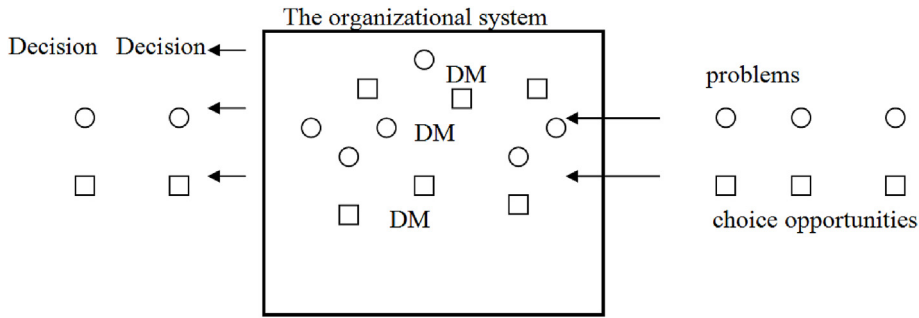


Fig. 1. A Conceptual Diagram of the Garbage-Can Decision-Making Process
 Note: DM = decision maker.

are thrown into garbage cans where decisions may or may not be made. If a decision is made in a garbage can as an output of the system, problems and choice opportunities attached to the garbage may disappear and leave the system.

Briefly speaking, based on the garbage-can model developed in an organizational choice context (Cohen et al., 1972; Lai, 1998, 2003; Padgett, 1980), the SGCM views the urban development process as a sequence of seemingly random meetings of five elements such that decision situations emerge and then decisions are made (Lai, 2006). These five elements are decision makers, decision situations, solutions, problems, and locations. Two characteristics distinguish the SGCM from other disaggregate models of urban development: it attempts to incorporate the interactions among both tangible and intangible entities, and it blends the environment (where decision events take place) and individuals (that trigger these events) into a single common framework. For example, decisions makers, roughly equivalent to agents, and locations are tangible entities, whereas decision situations, solutions, and problems are not. The interaction between decision makers and locations implies that the environment and the set of individual behaviors mutually affect each other.

The SGCM does not imply that the seemingly random meetings of the five elements occur without constraints. In the SGCM, four structural constraints (access, decision, solution, and spatial structures), which are reminiscent of organizational structures of institutions, are imposed on the system. In this framework:

- The access structure specifies which problems can be solved in which decision situations.
- The decision structure identifies which decision makers can attend which decision situations to make decisions.
- The solution structure depicts which solutions can be used to solve which problems.
- The spatial structure clarifies which decision situations can be linked to which locations.

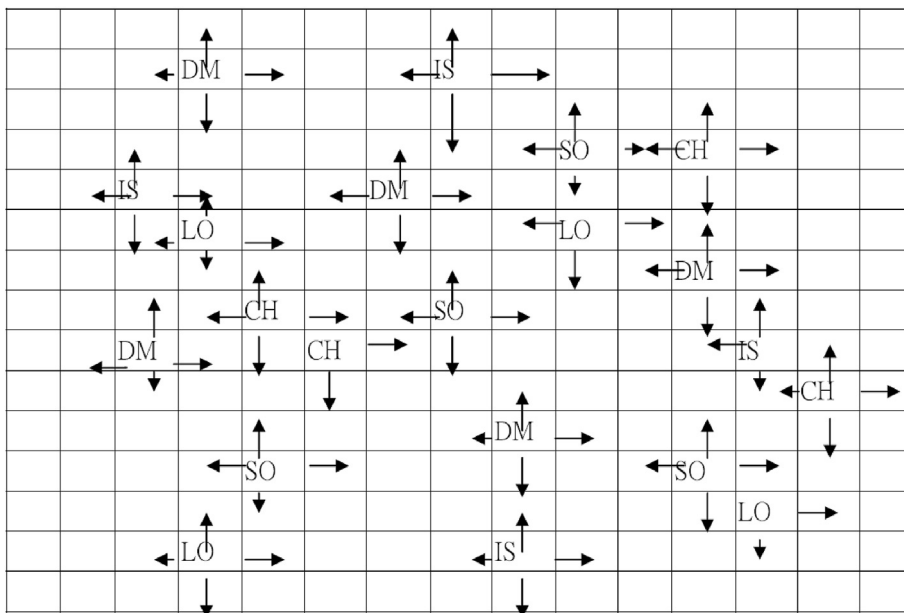


Fig. 2. A Two-Dimensional Representation of the SGCM
 Note: DM = decision maker; SO = solution; IS = issue; CH = choice; LO = location.

All these structures create formal and informal constraints in the complex urban system to restrict which decisions can be made when, where, and by whom. Our initial observation of a simulation run of the SGCM implies that the traditional notion of focusing on spatial design, such as spatial structure, to improve the performance of the complex urban system is not as effective as emphasizing institutional design, such as access structure (Lai, 2006). The conceptual framework of the SGCM is so rich that many important concepts of the urban development process can be incorporated into the model to explain real urban phenomena that are not easily obtained from traditional aggregate urban models.

A grid system in which the five elements flow to and mix with each other can be used to represent the SGCM spatially and to make the concept more concrete (see Fig. 2). These elements are linked to one another in different ways. At each time step, an element of each type emerges randomly in the grid system, and these elements flow randomly in four different directions and advance one cell further for the next time step. When the supply of energy (similar to the resources available) exceeds the demand (similar to the costs of taking actions) at a particular location for a particular choice opportunity, a decision is made. If there are problems associated with the choice opportunities and the criterion of energy deficit is met, these problems are solved. Energy is used here as a metaphor for the resources and capabilities available to solve problems in a decision situation, such as labor, capital, land, time, and the analytical skills of a developer investing in development. Investment in such resources and capabilities is required in order to solve problems. Therefore, energy deficit or surplus represents the difference (negative or positive) between the energy levels that are required and those that are available in a decision situation.

The urban development process can be characterized by interdependence, irreversibility, indivisibility, and imperfect foresight (Hopkins, 2001). Interdependence means that the outcome of one decision depends on another decision. Irreversibility means that it is costly to change a decision previously made and implemented, which precludes costless dynamic adjustment. Indivisibility means that a development decision cannot be made with arbitrary increments, which implies scale economy. Imperfect foresight simply recognizes that uncertainties cannot be totally eliminated in making plans. These four Is render the well-known equilibrium analysis based on neoclassic economic assumptions unrealistic but are important matters in urban development planning. The importance of this argument is partially proved analytically (Lai, 2018) and can be further explored using the conceptual model presented in this editorial.

It is our intention to use the SGCM to test the previous argument empirically with the help of computer simulations. For example, irreversibility and indivisibility are special cases of interdependence in that development decisions are related in time and space in terms of cost and scale. These three Is can be defined concretely in the simulation and formulated in the SGCM, such that the effects of planning and exogenous/endogenous disturbances can be tested and investigated. Making plans and policies can be defined in this context as predicting, selecting, and activating in decision situations, minimizing the net energy deficit that serves as an indicator of the system's performance.

3. Translating the spatial garbage-can model to constrained generating procedures through networks

This editorial presumes that cities are complex systems and that emergence is the hallmark of these systems. Many complex systems exhibit emergence, and we have just begun to recognize its existence and discover its laws or reinterpret the world from this new perspective (e.g., Laughlin, 2005). One way of investigating emergence is through constructing a general setting so that many complex systems, including cities, can be embedded in that setting. The urban model proposed in this editorial is constructed based on such a setting provided by Holland (1998).

3.1. Constrained generating procedures

A CGP is composed of a set of interacting mechanisms, each of which has states, inputs, and transition rules (Holland, 1998). For example, the game of checkers is composed of a set of mechanisms (squares) with pieces occupying them as states over time as the game unfolds. Collectively, these mechanisms form various configurations which are not arbitrary but are subject to rules governing moves as transition rules. This set of mechanisms, states, inputs, and transition rules constitutes a CGP whose behavior is complex and difficult to predict. There can be hierarchical levels of CGP, with the mechanisms on one level serving as the building blocks for the mechanisms on a higher level. Holland (1998) argues that many complex systems can be modeled this way to investigate emergence and shows how the

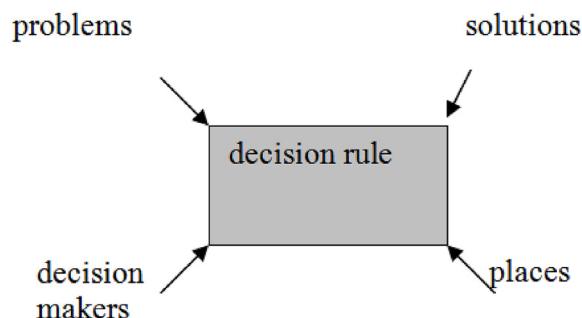


Fig. 3. The building blocks of the urban model.

notion of CGPs works for checkers, neural networks, CA, and the game of life, among others. We argue that cities are complex systems and can also be modeled by CGPs, as is briefly shown below.

3.2. Embedding the spatial garbage-can model in constrained generating procedures through network science

A garbage can be considered as a mechanism in order to embed SGCM in CGPs through network science, as shown in Fig. 3. Collectively, these garbage cans form the building blocks of our urban model, as Fig. 4 shows.

In the mechanism, problems, solutions, decision makers, and places are the four inputs; decision rule is the transition rule; and the gray box is the mechanism itself, whose state can be either a decision or no decision. A city can be represented by many such interconnected mechanisms (see Fig. 4). For example, a CGP is a set or network of such interconnected mechanisms, which in turn serves as a building block for another CGP on a higher level. An individual is a fundamental mechanism, and a few of them form a network of families and firms, which in turn constitute a community, as shown in Fig. 4. Note that such a construct can also be represented mathematically (Holland, 1998).

The network of decision situations as a manifestation of CGPs can be modeled as a cellular automaton. Using this combined network model of CA, CGPs, and SGCM, or SGCM/CGP/NW, we can investigate the dynamic characteristics of the evolution of the combined network model under various configurations. Following Watts and Strogatz (1998), we can start with a “regular” configuration in which each cell representing a decision situation is connected locally only to its eight neighbors, then progress to a “small world” configuration in which a few arcs link some randomly chosen cells forming sparsely connected clusters, and finally consider a “random” configuration in which each cell is randomly connected to some other cells (see Fig. 5). Through computer simulations, we can then observe and compare the patterns of evolution of these configurations using space–time plots to determine where order could emerge from such simulations. In addition, using real cases of urban development, such as New York, London, and Taipei, we can investigate whether development decisions are connected as small world configurations. The results would give us insights into how to manage and plan patterns of urban development.

In addition to garbage cans as the building blocks of a city, there is an emergent web of plans presenting as agendas, policies, visions, designs, and strategies that interact with a given city (Donaghy & Hopkins, 2006; Hopkins, 2001). An agenda is a list of things to do, a policy is an if–then rule, a vision is an imagined future that motivates action, a design is a well thought-out outcome to aim for, and a strategy is a contingent set of related decisions or a path in a decision tree. These plans can also be represented by a set of fundamental mechanisms (see Fig. 6). For example, an agenda is a list of garbage cans, whereas a strategy is equivalent to a decision tree with decision nodes replaced by garbage cans, as shown in Fig. 6.

Given the above conceptual construct of a coupled planning and urban system, we can run simulations to discover possible laws of urban emergence. For example, is it true that the scales of CGPs on a particular level can be characterized by a power law distribution? Is a set of hierarchical comprehensive plans more effective than a web of emergent plans of different scopes?

4. An experimental design

We can use the SGCM/CGP/NW model to explore how institutions come about and how they interact with plans, given a certain configuration of CA of the complex urban system. For example, we can hypothesize that institutions as manifestations of structures in terms of the relationships among decision makers, problems, decision situations, solutions, and places can arise more easily in the “small world” configuration than in the “regular” and “random” configurations. We can also hypothesize that plans and institutions complement each other in that the more plans are made, the fewer institutions emerge.

In order to test the hypotheses, we can conduct an experiment of a three-factorial design with an investment in plans i , a probability of links p , and an index of decision cost c as the three factors under consideration. Plan investment i is defined as the clustering of plans, with $i = 0$ meaning no plans at all and $i = 1$ meaning one comprehensive plan. When $0 < i < 1$, plans are clustered, meaning that there are many interacting plans. The probability of links p is defined as the clustering of decision situations or cells in CA, with $p = 0$ meaning the “regular” configuration and $p = 1$ meaning the “random” configuration. The “small world” configuration can be represented as one where $0 < p < 1$. Decision cost c is the cost associated with a decision situation when a decision is made. It is an index of transaction cost. Using i , p , and c as three controlled variables, we can conduct a set of computer simulations to observe how the system evolves and how institutions emerge, given a combination of plan investment, probability of links, and decision cost.

Institutions are manifested as the structures of the decision maker/decision situation relationship (decision structure), the problem/

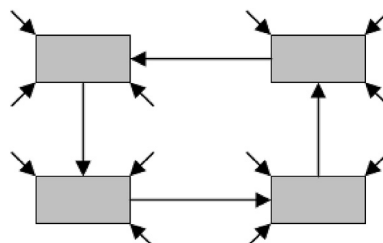
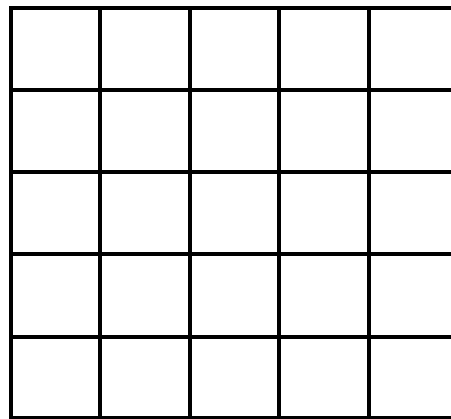
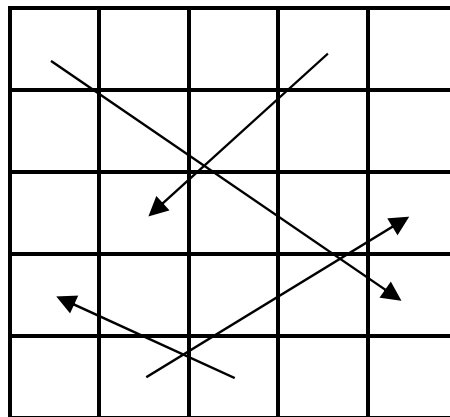


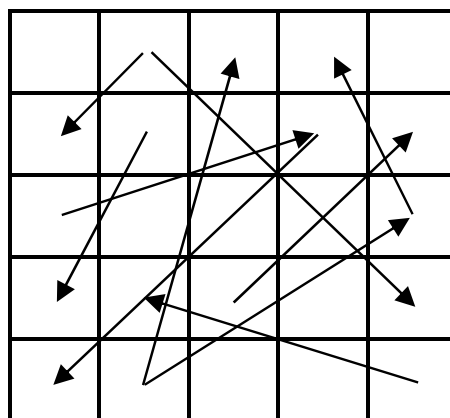
Fig. 4. Networks of mechanisms.



“Regular” configuration



“Small world” configuration



“Random” configuration

Fig. 5. Different spatial Configurations.

decision situation relationship (access structure), the problem/solution relationship (solution structure), and the decision situation/ places relationship (spatial structure). These structures can be represented as zero–one matrices, with one meaning that the element in the row is connected to the one in the column. These structures co-evolve internally with the system, so we can observe whether order

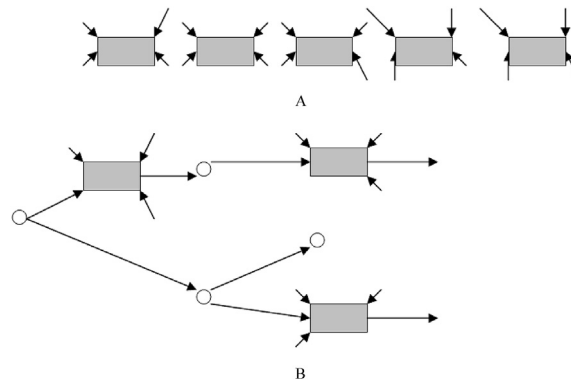


Fig. 6. Representation of plans as agendas (A) and strategies (B).

emerges from the simulations, given different combinations of plan investment, linking probability, and decision cost. The order of these structures reminiscent of institutions can be computed based on an entropy index, where the higher the value of the index, the lower the order of the structural configuration, thus the less significant the institutional structures (e.g., Lai, 2022).

The findings and implications derived from the experiments can be readily used to explain urban development in China. For example, before 1979, when a planned economic policy was strongly imposed, meaning that i is close to one, we can expect that fewer institutions emerged because plans and institutions are complementary. After 1979, when economic reform commenced, meaning that i is less than one, we can expect that more institutions emerged for the same reason. We can also expect that with an increase in decision cost c , plan investment i would also increase because of the irreversibility of decisions (Hopkins, 2001).

The experimental results also provide insights into policymaking in urban development situations in China. For example, we can summarize the simulations to pinpoint an ideal level of plan investment i so that at a certain level where $0 < i < 1$, the urban system's performance is optimized, implying that having a few plans works better than having no plan or only one comprehensive plan (Hopkins, 2001). Furthermore, the experimental simulations suggest that institutional structures affect the system's performance more than physical design does. Accordingly, a balance between institutional structures and physical design should be emphasized in urban planning, rather than a sole focus on physical design, as is commonly practiced in China. In addition, we can observe from the simulations how policies that change transaction costs, manifested as decision costs in the model, can affect the system's performance, compared to plan investment and linking probability. For example, the internet and telecommunication technologies developed in China would reduce transaction costs, which would in turn make the urban development process more efficient.

5. Conclusions

Emergence is the hallmark of urban dynamics, most notably clustered activities. Computer simulations are an effective tool for analyzing complex urban systems. Plans and cities are loosely coupled in the urban development process. In this editorial, we propose a conceptual model to blend tangible and intangible entities in a complex urban system into a common framework. We also propose an experimental design for such computer simulations based on the common framework in the context of urban development in China. Much can be gained from such endeavors.

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