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A spatial garbage-can model

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Abstract. In this simulation, based on a spatial garbage-can model, I treat the urban dynamic system as a set of random-walk elements interacting with each other in time. Five elements are considered: decisionmakers, choice opportunities, problems, solutions, and locations. Decisionmakers, problems, and solutions meet in an unpredictable way, are thrown into garbage cans as choice opportunities in certain locations, and something happens. In contrast to most traditional spatial simulation techniques, in which space is global and static, I consider in this simulation locations of facilities as dynamically floating on the stream of opportunities, interacting with other elements. The simulation results imply that the relationship between problems and choice opportunities dominates the outcome of the evolution, whereas the effects of the spatial structure as well as the structures of decision and solution are insignificant. The model may provide useful insights into how urban dynamics evolve.

1 The city as an organized anarchy

The urban development, or spatial, process is composed of at least two sets of interrelated spatial decisions: investments in facilities and activities taking place in and between these facilities. In addition, there exist a set of rules, formal – informal and spatial – nonspatial, as the constraints imposed on the discretion of these decisions. There are of course many interacting actors making these decisions. It should arguably be true that cities are collectives of accumulated stock of such facilities, which result from numerous interacting development decisions made both by the public sector and by the private sector. These decisions are interrelated functionally, geographically, and institutionally. Various activities that take place in cities are affected by the locations, densities, and types of these developments, and influence in return where, when, and how development decisions are implemented. There is no apparent order and collective intention as to how these decisions are made and how they interact with each other. Modeling such mechanisms on the basis of a conceptually sound framework may help not only to understand how the urban development process comes about, but also to provide useful insights into how to make effective plans for the process.

Traditional transportation and land-use mathematical models treat all the actors of these decisions, such as households and landowners, the same, and apply statistical techniques, such as regression analysis, to construct and calibrate an aggregate, representative behavioral model to fit the empirical data. Though these models are useful to some extent in making forecasts about the urban development process, the underlying mechanisms of how these actors interact in cities and how individual differences play out in the evolution of urban development are largely ignored.

The recent surge of the agent-based modeling approach provides a useful alternative for urban modeling, thanks to the advance of computing technology, in that the spatial interaction among these actors is explicitly recognized and the properties which emerge from urban spatial evolution are simulated, observed, and interpreted (for example, Benenson and Torrens, 2004; Parker et al, 2003). Though the agent-based modeling approach to urban phenomena looks promising, most works in this line of research focus on the investment decisions of cities, such as where, and what type of land use, to develop, ignoring the activities decisions of the actors as to where to act and what actions to take. The model presented in this paper is intended to provide a simulation framework in which investment and activities decisions and their interactions are accounted for, given some institutional structures that set the constraints for how these decisions interact. The model presented is by no means complete in modeling urban phenomena, but it shows how investment and activities decisions within some institutional structures can be blended into a coherent whole that captures the essence of the urban development process.

To elaborate the urban development process in more detail, I first consider investment decisions. The complexity of intertwined development decisions defies any theoretical explanation that focuses only on orderly sequences, but we can at least understand the process by viewing the emergent development pattern as being derived from the interplay among five almost independent streams of elements, namely decisionmakers, solutions, problems, decision situations, and locations (see, for example, Cohen et al, 1972). Decisionmakers are actors or developers in the public or private sector who seek appropriate lands to develop. Solutions are lands and capitals or any other resources that can help realize the development decisions. Problems are the gaps between what decisionmakers anticipate and what the current status is of the situations under consideration. Decision situations are occasions on which development decisions are attended to and may or may not be made. Locations are associated with lands on which developed facilities are built. An emergent development decision is derived from a seemingly random meeting of decisionmakers, solutions, problems, and locations in a particular decision situation in which all the other four elements happen to match each other to reach a consensus among the decisionmakers involved. A developer might initially have lands available, but would not know what to do about them. When opportunities arise, such as low interest rates, emerging accessibility to major streets, and increased land values, the developer, along with other participating partners, such as landowners, might decide in a meeting to develop the land in that particular location in the hope of yielding profits. There is no clear, definite, and causal relationship between the elements, owing to the complexity of the interaction among them. Solutions might already exist before problems arise at later times. Decisionmakers look for work. Problems look for decision situations in which they can be discussed.

Now consider activities decisions. Cities are full of changing events, which can be seen as changes in status quo. Events trigger activities. For example, the initiation of services provided by business owners affects households' choice of where to locate, which store to go to, where to work, which restaurant to dine in, which movies to go to, which hospital to visit, which route to take, and which school to attend, to name just a few examples. Each emergent activity, routine or nonroutine, is also derived from a complex of intertwined decisionmakers, solutions, problems, decision situations, and locations. In deciding where to shop and what to buy, for example, the household might first have funds available and be looking for stores offering different goods in various locations. With traveling capability through network facilities, and within a particular store, they will select a particular good with a reasonable price that meets their needs, and an exchange decision is thus made. When decisionmakers, solutions, problems, and decision situations meet in a seemingly random form in a particular decision situation, an activity decision may or may not be made, depending on whether the four elements match each other in that particular decision situation. The crux is that there is no clear, definite, and causal relationship between the five elements, owing to the complexity of the interaction among them. Each stream of elements seems independent of the others. Chances reign, in part, in the occurrences of such events and thus in the making of activities decisions.

Investment decisions and activities decisions interact with each other. A successful highway investment would attract more travel activities in terms of trips, which in turn would affect the land uses near the interchanges located along the highway. The traditional dilemma of transportation and land-use planning is a case in point.

Given the same interpretational elements of how investment and activities decisions emerge, at a more fundamental level, the urban development process as a whole can be characterized by the meeting of decisionmakers, solutions, problems, and locations in particular decision situations, and by something happening, whether it is a development of facilities or an initiation of activities. Note that investment and activities decisions are constrained by a set of formal or informal rules or institutions. Zoning is a good example. It specifies what type of development is allowed, where, and with what densities, which in turn determine what activities can be carried out in that particular location. For example, in a residential zone, apartments or similar facilities can only be built for dwelling purposes, with other uses prohibited.

With such a simplified conception of urban development process in mind, the simulation presented in the present paper is grounded on the presumption that a city can be viewed as an organized anarchy of loosely coupled components, in which five streams of elements—decision situations, decisionmakers, problems, solutions, and locations—interact in an unpredictable way in time within certain organizational or institutional structures. Decision situations and choice opportunities, as well as problems and issues, are used interchangeably. This conception is based on Cohen et al's (1972) garbage-can model of organizational choice behavior. Though the garbage-can model was created to describe descriptively how decisions are made in organizations, its framework has been applied in other complex systems, mainly in public administration of political systems, in which the interaction of the elements seems random and chaotic (see, for example, Kingdon, 2003). Unlike in the case of cities, there is no consideration, however, of spatial elements in these complex systems, such as agenda setting in a political system.

With this simplified mindset concerning the urban development process, I formulate a simulation of the dynamics of the spatial evolution of the city on the basis of the garbage-can model, which will be called the spatial garbage-can (SGC) model. I treat each actor as a decisionmaker who encounters a stream of problems, such as where to shop or where to look for housing; a stream of solutions, so that these problems can be attached to suitable solutions, such as shopping malls and apartments; a stream of decision situations in which decisions are made, such as regular meetings and informal encounters with colleagues; and a stream of locations at which activities or investments might be located as a result of decisions. This conception is arguably an overly simplified view of the city, but rather than decomposing the urban system into independent, functional parts, as most traditional models usually do, or regarding the actors and their environment as separate entities, the simulation attempts to blend all the seemingly unrelated elements into a coherent framework through which interesting, counterintuitive phenomena can be uncovered. Therefore, in the present paper I focus on how urban dynamics can be perceived descriptively, rather than how we should plan to improve situations. Such attempts are reported elsewhere on the basis of the original garbage-can model (for example, Lai, 1998; 2003), and will be made in the future on the basis of the proposed SGC model.

In the present paper I will construct the elements of this simulation framework in sequence and report the results. Section 2 contains a description of the garbage-can model. In section 3 I explain how the spatial elements can be incorporated into the garbage-can model. In section 4 I report the design and results of the simulation. Section 5 contains a discussion of some implications, possible applications, and future extensions of the SGC model. In particular, suggestions as to how planning is defined and incorporated into the SGC model will be offered. Conclusions are drawn in section 6.

2 The garbage-can model

The original formulation of the garbage-can model of organizational choice considers four independent elements: choice opportunities, solutions, problems, and decisionmakers (Cohen et al, 1972). Choice opportunities are situations in which decisions can be made, that is, commitments to actions are made. In organizations votes to spend money or signatures on forms to hire or fire persons are examples of choice opportunities. Solutions are actions that might be taken, such as persons who might be hired, tax schedules that might be levied, and land developments that might be approved. Solutions are things that choice opportunities can commit to enact, things we have the capacity to do directly. Problems are issues that are likely to persist and that decisionmakers are concerned to resolve, such as homelessness, unfair housing practices, congested highways, or flooding. Note that choice opportunities enact solutions and that they do not solve problems. We cannot merely choose not to have homelessness. We cannot 'decide a problem'. We can choose to spend money on shelters or to hire social workers, which may or may not affect the persistence of homelessness as a problem. Decisionmakers are units of the capacity to take action in decision situations (Lai and Hopkins, 1995).

A garbage can is a choice opportunity in which the elements meet in a partially unpredictable way. Solutions, problems, and decisionmakers are thrown into a garbage can and something happens. There is, however, no simple mapping of decisionmakers to problems or of solutions to problems. Further, an organization has many interacting garbage cans, many interacting choice opportunities. The original model was used to investigate universities as an example of 'organized anarchy'. Structure can be increased from this starting point, however, which makes possible the investigation of a wide range of types and degrees of organizational structure (see, for example, Padgett, 1980). Planning and organizational design are at least partially substitutable strategies for affecting organizational decisionmaking. They are both means of 'coordinating' related decisions. Thus the garbage-can model provides a useful starting point for investigating planning in organizations (Lai, 1998; 2003). The major assumption of the model is that the streams of the four elements are independent of each other. Solutions may thus occur before the problems that these solutions might resolve are recognized. Choice opportunities may occur because regular meetings yield decisionmaker status, independent of whether solutions are available.

With this general formulation, Cohen et al (1972) ran a simulation addressing four variables: net energy load, access structure, decision structure, and energy distribution. Net energy load is the difference between the total energy required for a problem to be resolved and that available from decisionmakers. Different net energy loads, roughly analogous to organizational capacity, in the form of decisionmakers, relative to organizational demand, should yield differences in organizational behavior and outcomes. The access structure is the relationship between problems and choices or choice opportunities. A zero–one matrix defines which problems can be resolved by which choices. Different access structures vary in the number of choices that can resolve particular problems. A decision structure defines which decisionmakers can address which choices and thus how the total energy capacity of the organization can be brought to bear in resolving choices.

Cohen et al (1972) reported their results with a focus on four statistics: decision style, problem activity, problem latency, and decision difficulty. The three decision styles were resolution, oversight, and flight. Resolution meant that a choice taken resolved all the problems that were thrown into the garbage can of that choice opportunity. If a decision was taken for a choice to which no problems were attached, it was classified as oversight. All other situations constituted flight. Cohen et al were able to demonstrate the sensitivity of organizational behavior to various access structures and decision structures. For example, the decision process was quite sensitive to net energy load. The reader is encouraged to consult Cohen et al (1972) for the detailed working of the garbage-can model in a computer program written in FORTRAN.

3 Incorporation of spatial relationships

Planning, in the context of urban development, both physical and social, must acknowledge the significance of spatial effects of association, cooperation, and competition. Recent work on spatial evolution behavior characterized as cellular automata provides one popular alternative for incorporating space to the kinds of simulations developed here. Such models represent spatial clusters of cities or regions in either Euclidean or fractal geometry (see, for example, Allen and Sanglier, 1981; Batty and Longley, 1994). They tend to view urban change from a global point of view and planners can manipulate parameters or objects in the models in order to affect how cities evolve. The SGC model developed in the present paper takes a different spatial perspective of urban processes in that the actors experience urban processes from a local point of view, and intend to solve problems incrementally by making related decisions, as will be discussed in more detail in section 5.

In his recent book, based on a metaphor of canoeing on a river, Hopkins (2001) argues for the adoption of the garbage-can model in order to describe the situations faced by a planner, or a stream-of-opportunities model. In such a model, decision situations are choices about actions which the planner has the capacity, authority, and opportunity to take; issues are things that the planner cares about; solutions are things the planner knows how to do; and decisionmakers are the people with the authority, capacity, and opportunity to take actions. These four streams of elements float around in a relatively unstructured way and their chance meeting may lead to decisions and actions. Hopkins explains how the metaphor of canoeing on a river is compared with the stream-of-opportunities model and how planning situations can be described in this way. A fifth element can be added to the intermingling patterns of the above relatively independent phenomena floating in a stream, namely the locations of lands and facilities.

In the traditional spatial modeling concept, from a global point of view locations at which actions are taken are fixed. For example, certain activities, such as shopping-mall retailing, are carried out in a particular location, such as a building on a parcel of land in the suburbs. Choice opportunities or decision situations in combination with other elements must concern certain locations so that decisions can be made about investments and activities occurring at those locations. Locations are thus an additional element that becomes available in the model in the same way that problems, issues, and decision situations do. Thus, as Hopkins (2001, page 32) argues:

> “A stream of opportunities model, built on the garbage can model of Cohen et al (1972), provides one way to think about plans in complex systems: a plan-making situation is a collection of interdependent, indivisible, and irreversible decisions looking for issues; a collection of issues looking for interdependent decision situations in which they might be pertinent; a collection of solutions looking for issues to which they might be an answer; and a collection of planners looking for work.”

It is also a collection of locations looking for decision situations in which these decisions, issues, and actors can be brought to bear.

To make the SGC model more concrete, a decision structure of relationships is defined in terms of a matrix between decisionmakers and choice opportunities, an access structure of relationships between problems and choice opportunities, a solution structure between solutions and problems, and a spatial structure between choice opportunities and locations. These zero–one matrices of relationships have the same meaning and range of forms as in the original garbage-can model and are provided external to each simulation run. The meanings of decision structure, access structure, and solution structure are given in the original garbage-can model. For example, assuming that there exist twenty problems and ten choice opportunities, there are three types of constraint in access structures—unsegmented, hierarchical, and specialized—as shown in matrices $\mathbf{A}_0$, $\mathbf{A}_1$, and $\mathbf{A}_2$, respectively [see equation (1)]. A ‘1’ entry in the matrices means that the problem in the corresponding row can be attended to in the choice opportunity for the corresponding column, whereas a ‘0’ means that there is no such relationship. In the unsegmented structure all active problems have access to any active choice opportunities; in the hierarchical structure important problems (upper part of the matrix) have access to many choice opportunities; in the specialized structure each problem has access to only once choice opportunity.

$$\mathbf{A}_0 = \begin{pmatrix} 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \end{pmatrix}, \quad \mathbf{A}_1 = \begin{pmatrix} 1111111111 \\ 1111111111 \\ 0111111111 \\ 0111111111 \\ 0011111111 \\ 0011111111 \\ 0001111111 \\ 0001111111 \\ 0000111111 \\ 0000111111 \\ 0000011111 \\ 0000011111 \\ 0000001111 \\ 0000001111 \\ 0000000111 \\ 0000000111 \\ 0000000011 \\ 0000000011 \\ 0000000001 \\ 0000000001 \end{pmatrix}, \quad \mathbf{A}_2 = \begin{pmatrix} 1000000000 \\ 1000000000 \\ 0100000000 \\ 0100000000 \\ 0010000000 \\ 0010000000 \\ 0001000000 \\ 0001000000 \\ 0000100000 \\ 0000100000 \\ 0000010000 \\ 0000010000 \\ 0000001000 \\ 0000001000 \\ 0000000100 \\ 0000000100 \\ 0000000010 \\ 0000000010 \\ 0000000001 \\ 0000000001 \end{pmatrix}, \qquad (1)$$

where the columns represent choice opportunities and the rows represent problems.

Similarly, the spatial structure can be constructed by the zero–one matrices as shown in $\mathbf{B}_0$, $\mathbf{B}_1$, and $\mathbf{B}_2$ [equation (2)]. A ‘1’ entry in these matrices means that a choice opportunity, such as the decision to construct a sewer line, can occur at a particular location, such as a transportation corridor, whereas a '0' indicates that such an association does not exist.

$$\mathbf{B}_0 = \begin{pmatrix} 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \\ 1111111111 \end{pmatrix}, \quad \mathbf{B}_1 = \begin{pmatrix} 1111111111 \\ 0111111111 \\ 0011111111 \\ 0001111111 \\ 0000111111 \\ 0000011111 \\ 0000001111 \\ 0000000111 \\ 0000000011 \\ 0000000001 \end{pmatrix}, \quad \mathbf{B}_2 = \begin{pmatrix} 1000000000 \\ 0100000000 \\ 0010000000 \\ 0001000000 \\ 0000100000 \\ 0000010000 \\ 0000001000 \\ 0000000100 \\ 0000000010 \\ 0000000001 \end{pmatrix}, \qquad (2)$$

where columns refer to locations and rows correspond to choice opportunities.

To 'visualize' the SGC model and to make the concept more concrete, consider a grid system in which the five elements flow to and mix with each other (see figure 1). Note that the grid system does not have any physical meaning; it is created only for visualization purposes for the process. There are five types of elements: decision situations (choice opportunities), decisionmakers, solutions, issues (problems), and locations, with access structure linking issues to decision situations, solution structure linking solutions to problems, decision structure linking decisionmakers to choice opportunities, and spatial structure linking choice opportunities to locations. At each time step, an element of each type emerges, located randomly in the grid system, and these elements flow randomly in four different directions one cell further for the next time step. When the supply of energy provided collectively by decisionmakers, solutions, and locations exceeds the demand required collectively by problems and choice opportunities, at a particular location and for a particular choice opportunity, a decision is made. If there are problems associated with the choice opportunities and the criterion of energy requirement is met, these problems are then solved.

Cities are complex spatial systems in which actors interact with each other spatially, and spontaneous order thus emerges regardless of the patterns of such interaction

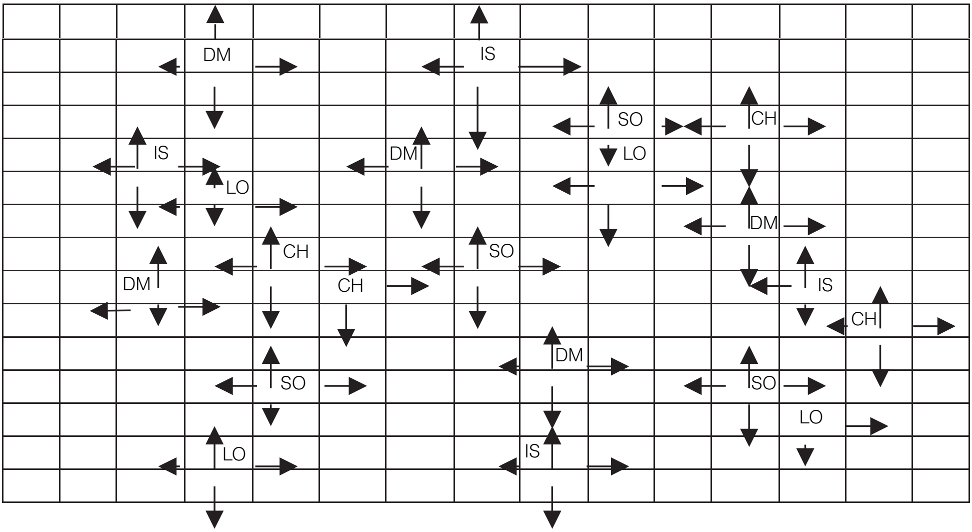

Figure 1. A visual representation of the spatial garbage-can model. DM: decisionmakers; SO: solutions; IS: issues; CH: choice opportunities; LO: locations.

(Webster and Lai, 2003). Viewing the complex spatial systems of cities as collections of elements interaction in an unpredictable, random way, I formulate a framework as described above in order for computer simulations to examine the effects of the structures on the behavior of the system. Put differently, following Cohen et al's (1972) garbage-can model, I consider the complex spatial system as a loosely coupled organization composed of five independent streams of elements: solutions, problems, decisionmakers, decision situations, and locations (see figure 1). These random-walk elements interact with each other in the two-dimensional grid system, and decisions may get made. Though the assumption of randomness of the five interacting streams might be too strong, the observation that the dynamics of the complex spatial system are usually considered as chaotic supports, at least partially, such a conception. Concrete examples as manifested in the SGC model are found on many occasions in the city, as sketched in section 1.

4 Simulation design and results

A simulation design of a Graeco-Latin square (Kirk, 1982) was run using the formulation discussed in the previous section. In particular, the grid system was composed of 50×50 cells, with 500 decisionmakers and 500 locations randomly occupying these cells initially. Solutions, problems, and choice opportunities were added to the system, one of each at a time, for the first 500 time steps. Decisionmakers, solutions, and locations were energy suppliers, whereas problems and choice opportunities were energy demanders. When at least one of each of the five elements met in a particular cell and the amount of energy supply associated with these elements was greater than that of energy demand, a decision was made. The associated problem(s) was solved and removed, as was the associated choice opportunity (opportunities).

In order to visualize the temporal trajectories of the evolution of the complex spatial system, a three-dimensional energy landscape space is defined in which the total net energy, the number of decisions made, and the number of problems solved form the three axes, as shown in figure 2. The total net energy of the system is computed by summing up all the energy supplied and subtracting all the energy needed

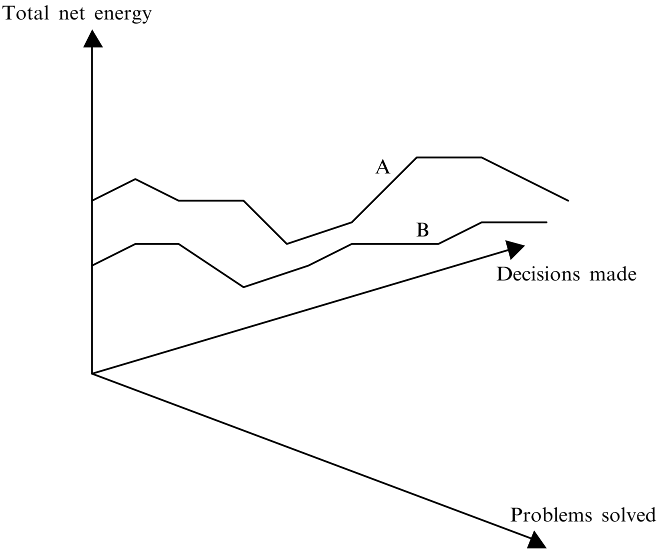

Figure 2. System trajectories in time in the energy landscape.

across all elements at a time step. In figure 2 curves A and B represent two dynamic trajectories of the complex spatial system in the energy landscape.

The amount of energy supplied was given randomly from 0 to 1 for each solution. The amounts of energy supplied by each decisionmaker and location were set to 0.55 and 2.55 respectively, and the amounts of energy demanded by each problem and choice opportunity were both set to 1.1. These numbers were chosen according to Cohen et al's (1972) original simulation, except that the energy supplied by each location was set to a higher value to reflect the importance of this element. Because these numbers were fixed in all simulations in the research design and thus not treated as control variables, a different set of these numbers would not have affected the simulation results. Total net energy refers to the difference between the total amounts of energy associated with all demanders and suppliers. The simulation was programmed using Visual Basic and ran on a Windows 2000 platform.

Figures 3(a) – (d) (see over) show the preliminary results from a pilot simulation based on the total net energy-time plot of the system. Figure 3(a) shows the result

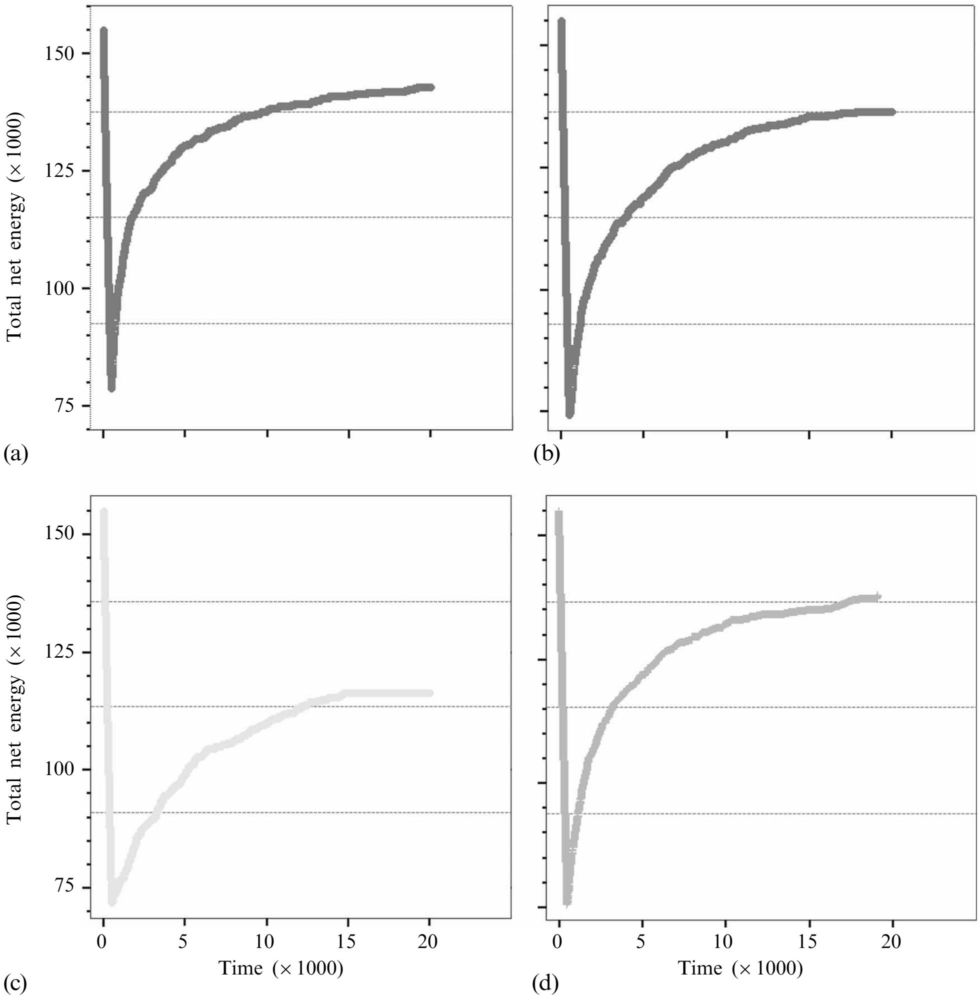

Figure 3. Total net energy – time plots for (a) unsegmented structures, (b) hierarchic structures, (c) specialized structures, and (d) random structures.

relating to the unsegmented type of constraint in access, solution, decision, and spatial structures. Figure 3(b) relates to the hierarchic type of constraint in structures. Figure 3(c) relates to the specialized type of constraint in structures. Figure 3(d) concerns the random type of constraint in structures. Each simulation was run for 20 000 time steps. Note that for each total net energy – time plot, we can compute statistically an asymptotic value that sets approximately the upper limit for the curve.

All trajectories show skewed 'v' shape curves in the sense that the total net energy decreased dramatically in the early time steps, and then regained its amount slowly in later time steps. This characteristic 'v' shape results mainly from the inflow pattern of the elements in the sense that problems and decision situations arrive initially, causing a drop in the total net energy because few decisions are made to reduce energy demand in the early stage; when, in later time steps, more decisions are made and more problems are solved, the system regains its total net energy because the demand for energy decreases. A change in the pattern of arrival of problems and decision situations or a change in the access or decision structures can be considered as a disturbance and will be discussed in more detail in section 5. The only difference between the curves is the steepness after the lowest point has been reached. The 'v' curves for the unsegmented structures seem the steepest among all four structures, and those for the specialized structures seem the flattest. Energy demanders, including problems and choice opportunities waiting to be solved and made, were added to the system incrementally, thereby decreasing the amount of the total net energy sharply in the beginning. At later time steps, when sufficient numbers of elements were added to the system, resulting in an increased likelihood of decisionmaking, the total net energy increased because more and more decisions were made and more and more problems were solved, which in turn lessened the energy demand. Structural constraints do seem to affect the shapes of the trajectories. In particular, more stringent structural constraints rendered the system less capable of adapting to the inflow of disturbances of problems, choice opportunities, and solutions. Put differently, more stringent structural constraints, such as the specialized structural type, reduce the likelihood that the five elements meet with each other and thus decrease the opportunities of making decisions to solve problems. The system becomes more insensitive to the effects of the inflow of elements. In the real world this observation can be likened to the contrast between a free-development market and a regulated-development market. In the free-development market, in which exchanges are not constrained, and which is reminiscent of an unsegmented structural type, the effects of external disturbances can be absorbed more quickly by the system, thereby making it more resilient than the regulated-development market. The observation that more stringent structural constraints render the system less able to adapt seems to be implied also by the original garbage-can model in that the specialized access structure results in a higher proportion of choice opportunities in which decisions are made only to resolve problems, which is a more difficult approach than other types of decision style (Cohen et al, 1972).

For completeness I designed a simulation of a Graeco-Latin square, consisting of sixteen orthogonal combinations of the four types of constraints (unsegmented, specialized, hierarchic, and random) with respect to the four structures (access, spatial, solution, and decision structures). The sixteen orthogonal combinations of the constraint types with respect to the four structural variables are given in table 1. Unsegmented, specialized, hierarchic, and random constraints are denoted as 1, 2, 3, and 4, respectively. A random constraint means that the 1s in a matrix are randomly assigned to the elements in that matrix.

A 20 000 time-step simulation was conducted for each of the sixteen combinations of the constraint types with respect to the four structural variables shown in table 1. For each of such simulation runs, I was able to compute, using SPSS (statistical package for the social sciences), the asymptotic value of the total net energy at the end of 20 000 time steps as an upper limit. These values are given in the four-factorial design of the 4 × 4 Graeco-Latin square as shown in table 2. Note that a, b, c, and d denote access structure, spatial structure, solution structure, and decision structure, respectively, and that 1, 2, 3, and 4 denote unsegmented constraint, specialized constraint, hierarchic constraint, and random constraint, respectively. For example, d_2, represents the decision structure with a specialized constraint. The number in each cell represents the asymptotic value of the total net energy for the simulation after 20 000 time steps, given the combination of different structures and constraints. For example, the number 154 783 in the cell of $a_1 b_3$ in row 2 (c_2) and column 2 (d_2) is the total net energy of the simulation result, considering the combination of access (a), spatial (b), solution (c), and decision (d) structures with unsegmented (1), hierarchic (3), specialized (2), and specialized (2) constraints, respectively, and is coded as 1322 in table 1.

Table 1. Combinations of constraint types with respect to structural variables.

Access structure	Spatial structure	Solution structure	Decision structure
1	1	1	1
2	4	2	1
3	2	3	1
4	3	4	1
2	2	1	2
1	3	2	2
4	1	3	2
3	4	4	2
3	3	1	3
4	2	2	3
1	4	3	3
2	1	4	3
4	4	1	4
3	1	2	4
2	3	3	4
1	2	4	4

Table 2. The four-factorial design of the 4 × 4 Graeco-Latin square.

	d_1	d_2	d_3	d_4
c_1	a_1b_1 143 440	a_2b_2 117 499	a_3b_3 135 603	a_4b_4 137 877
c_2	a_2b_4 135 417	a_1b_3 154 783	a_4b_2 138 176	a_3b_1 134 963
c_3	a_3b_2 137 576	a_4b_1 137 106	a_1b_4 141 200	a_2b_3 117 070
c_4	a_4b_3 135 603	a_3b_4 131 700	a_2b_1 117 004	a_1b_2 137 702

Following Kirk's (1982, pages 314–316) computational procedure for a 4 × 4 Graeco-Latin square, I was able to compute the analysis of variance (ANOVA) table for this design as shown in table 3. Note that, because there is only one observation in each cell, the significance of the effect of the interaction term cannot be tested.

According to the ANOVA table, the main effect of access structure was statistically significant at $p < 0.05$, whereas the main effects of the other three structures were insignificant. We can conclude that the relationship between problem and choice opportunities is of paramount importance in the determination of how the system behaves, whereas spatial structure, solution structure, and decision structure do not affect the performance of the system in terms of the total net energy. This conclusion is drawn partly because problems and choice opportunities are the only two energy demanders, and the relational structure between the two elements—that is, the access structure—plays a central role in determining whether a decision is made in a particular choice opportunity and whether the associated problems are resolved in order to reduce the energy demand, which consequently increases total net energy. As depicted earlier, a change in the initial setting of energy levels would not change the simulation result because these values are constant across all combinations of structures in the simulations. Similarly, different types of access structure would not change the result as long as they and other structural constraints are held constant throughout the simulations. The implications of this result will be elaborated in more detail in sections 5 and 6.

Table 3. The analysis of variance table for the Graeco-Latin square design.

Source	Sum of squares	Degrees of freedom	Mean square	*F*
Access structure (a)	1 062 967 500	3	354 322 500	15.1420*
Spatial structure (b)	43 093 200	3	14 364 400	0.6139
Solution structure (c)	233 988 500	3	77 996 167	3.3333
Decision structure (d)	87 632 700	3	29 210 900	1.2483
Residual	70 199 800	3	23 399 933	
Total	1 497 881 700	15		

* Significant at $p < 0.05$.

5 Discussion

The original garbage-can model is concerned with decisionmaking in an organizational setting. It differs from traditional decision theory in that it is descriptive rather than normative. It is grounded on a limited rationality of decisionmaking rather than perfect rationality. It addresses organizational choice behavior rather than individuals making decisions. It tries to make sense of the seemingly chaotic, collective processes of fragmented decisionmaking in an organizational setting in which central planning is absent. In sum, it describes how an organized anarchy adapts to the changing environment in order to survive, albeit without central planning.

The intermixing of the elements in the garbage-can model is not purely random; there are some structures imposed on the chance meeting of the elements, namely access structures and decision structures. An access structure determines which problem can be attended to in which decision situation, and a decision structure specifies which decisionmaker can join which decision situations to make decisions. The combination of the two can be viewed as an institutional structure that allocates the rights as to which decisionmaker has what authority to resolve which problem through which decision situation. Thus, a decisionmaker, within the context of the garbage-can model, is not exposed to any solutions, or any options. His or her discretion of making decisions is somewhat constrained.

The extension of the garbage-can model to a spatial context, as proposed in this paper, is not meant to model planning behavior itself, but to model urban-development processes. These two phenomena beg two different theoretical underpinnings, but elaborating on the distinction between the two is beyond the scope of the paper. Put simply, the SGC model can be treated as a descriptive manifestation of how urban spatial dynamics evolve, whereas a planning theory can be narrowly thought of as a behavioral theory of how to make interdependent decisions, or plans. Given this simple distinction, we can thus provide a theoretical basis, using the SGC model, on which the effectiveness of different planning theories can be examined. For example, is incrementalism (focusing on no rationality), which renders planning useless according to some scholars in public administration, more effective in solving urban problems than comprehensive rationalism (focusing on perfect rationality), as suggested by conventional planning theorists? By imposing different degrees of structure or control on the dynamics of the SGC model representing the incremental – rational spectrum, we might find that something in between the two extremes (focusing on bounded rationality) might be more effective (Hopkins, 2001). Conventional planning decisionmaking models are essentially normative and are based on perfect rationality, through the assumption that actors have clear preferences, known technology, and a complete set of alternatives to choose from, whereas the garbage-can model is, in effect, descriptive and is based on bounded rationality in the sense that actors' preferences are problematic, technology is unclear, and alternatives are created. That is, the garbage-can model is designed on the basis of empirical observations of how organizations *do* make decisions, rather than how they *should* make decisions. From a descriptive point of view the garbage-can model is therefore behaviorally more telling than conventional, normative planning decisionmaking models. In the making of a development decision, can the developer know for certain what other actors would do when, and where and how they interact? In addition, conventional planning theories do not seem to take into account the differences between the behaviors of spatially disaggregate actors because the urban models on which these theories are developed tend to assume homogeneous actors. The SGC model proposed here decomposes the urban system into individual actors and related elements that mimic the real-world situations. Loosely speaking, the SGC model is reminiscent of an agent-based modeling approach to urban phenomena, so the main logic of such an approach, in contrast to the traditional, mathematical urban modeling approach, applies here (see, for example, Benenson and Torrens, 2004; Parker et al, 2003).

The mechanisms underlying the model might sound counterintuitive at first to traditional decision theorists and planners, but empirical findings have shown that the model at least captures well the essence of the fragmented agenda-setting processes in the US federal government (see, for example, Kingdon, 2003). Whether this same theoretical framework works empirically for the urban development process remains as an interesting future-research question, but I suspect that, as described in section 1, cities could be viewed as spatial organized anarchies characterized by the garbage-can decision processes. For example, if we replace the agendas of a political system in Kingdon's model of agenda setting with development decisions of an urban system, some of Kingdon's explanations of how agendas emerge in a complex system could be applied to describe, at least in part, how development decisions emerge in the urban development process. For example, a city manager may have development proposals available and may be looking for a 'policy window' as a decision situation comes up, such that a development project is approved. However, a crucial distinction between an agenda and a physical facility is reversibility, in that the cost of reversing an agenda might be much lower than the cost of reversing a building. Regardless, the dynamic processes of the two systems might share some common theoretical underpinnings characterized by the garbage-can model.

If my presumption as set out in section 1 is true—that cities are spatial organized anarchies—we can start looking for ways to explain plan-making behavior consistent with the garbage-can notions. I have tried to do so in an organizational, not spatial, setting (Lai, 1998; 2003). In these two works, based on the original garbage-can model, I considered planning as a process of predicting the occurrences of the upcoming choice opportunities and intentionally selecting those that maximize the net energies in the associated decisions. Energy, as used in the SGC model, could be explained as benefits, profits, revenues, utilities, labors, capitals, or any other measurable resources in urban development situations. This strategy of incorporating planning into the garbage-can model is consistent with the idea that making plans implies evaluating related decisions and acting accordingly in light of the relationship between current and future decisions (Hopkins, 2001).

Decisionmaking focuses on choosing the best alternative from a given set, whereas planning, narrowly defined here, arranges for a contingent path of related decisions in time and space, or linked decisions. Though decision theorists recognize the importance of considering linked decisions, little has been said on how, and under what situations, a set of linked decisions should be analyzed (Keeney, 2004). Planning is thus obviously more challenging than decisionmaking, because it deals with uncertainties, values, and conflicting objectives which are much more complex than in the case of the latter.

Given this narrow definition of planning, there are at least two ways for the planner to make progress in the SGC model in terms of affecting the performance of the system. On the one hand, the planner could focus on anticipating possibilities of the occurrence of choice opportunities, arranging them in time and space before taking the first action, that is, making plans before acting. For example, to resolve a transportation and land-use problem in an urban area in which negative externalities pervade, such as congestion and pollution, the planner could look for decision situations in which decisions can be made regarding the construction of transportation networks that could alleviate the congestion issues, while taking into account the decision situations in which rezoning is possible to mitigate the pollution issues. He or she could even intentionally create other decision situations such as the budgeting of appropriate timing, if necessary, in order to address the pressing issues by persuading relevant governmental officials, citizens, and developers to resolve collaboratively other problems in sequence or jointly, leading to the resolution of the two problems under consideration. On the other hand, the planner could make changes in institutional structures in order to reassign the rights to limit actions, and in turn affect the outcome of the urban development process. For example, in order to create walkable communities of a city, which, it is claimed by the New Urbanist, will increase social capital, changes in institutional structures might be a more effective means than physical designs. We could enhance social equity, not simply by providing approximately equal physical accessibility to streets, but by allocating rights-of-way to all individuals equitably through regulations, such that all individuals have approximately equal rights to travel through the network, which will lead, in turn, to approximately equal authority to use facilities through accessibility and thus to approximately equal changes of carrying out activities to meet personal needs. The implication is, as derived from the simulation result, that spatial issues, such as the transportation and land-use problems and the New Urbanist's claim of walkable communities, could be addressed more effectively through the design of institutional structures than by merely focusing on physical layouts. Note that the institutional structures implied by the unsegmented, specialized, hierarchic, and random structural types do not fully carry realistic connotations in the simulation. They are designed mainly to distinguish different patterns of structures and to test the significance of structural effects on the evolutionary outcomes of the system. It is arguably true that zoning and permit systems which lead to different patterns of urban development are sufficiently distinct.

The 'v' shape of the trajectories in the energy landscape can be seen as a result of external disturbances to the system. When problems, choice opportunities, and solutions are added to the system incrementally, this sequence of elements flowing into the system can be considered as a set of external disturbances to the system, resulting in a dramatic drop in the total net energy. Eventually, when decisions are being made and problems are being solved, the system regains its stability to sustain itself and to function smoothly again, as evidenced by the slow asymptotic increase in the total net energy to a steady level. This behavioral characteristic can be used to model a wide range of external disturbances to the complex spatial system, such as changes in institutional structures owing to regulation implementations. When the land-control measure of an urban area is shifted from zoning to permit systems, the system may undergo a sea change in terms of its underlying structures, such as access structure, spatial structure, solution structure, and decision structure, perhaps from a hierarchic type to a random structural type. The random nature of the interaction among the elements remains, however, the same. We can test, using the SGC model, how well the system adapts to such disturbances in order to sustain its level of total net energy, given these structural changes, and which structural schemes of the system would result in minimum disturbances in terms of energy fluctuations.

Finally, the simulations presented here and elsewhere (Lai, 1998; 2003) assume that the structural constraints are fixed and given externally, thereby limiting the explanatory power of the SGC model. Regulations emerge as cities evolve, so it is arguably true that these structures coevolve with the system being simulated—that is, such structures are at present fixed at the unsegmented, specialized, hierarchic, and random types. If left to coevolve with the system, the spatial structure might result in spontaneous order as a form of spatial correlation of decision situations. Similar effects might occur if we introduce the notion of transaction cost in making decisions in garbage cans. That is, if decisions are costly in the combination of decisionmakers, problems, solutions, decision solutions, and locations, reducing that cost is desirable, resulting in systematic, rather than random, behaviors of actors. These systematic behaviors might be reflected by the structural patterns of the constraints in the form of association, cooperation, or even competition, if these structures are left to coevolve with the system. However, the underlying chance meeting characteristic among the elements remains the same. I extended the garbage-can model into a consideration of decision cost, similar to the notion of transaction cost in the combination of elements, on the basis of a three-factorial simulation design (Lai, 2003), and the results showed that all three factors, that is, planning investment, decision cost, and problem disutility, matter in terms of affecting the system's behavior. However, transaction cost is more pertinent to the spatial context formulated here (Webster and Lai, 2003), and can be incorporated into the model in the future.

6 Conclusions

Traditional and recent spatial modeling considers adaptive actors separately from their environment. In the simulation presented here, the spatial elements of the environment and the actors are blended into a partially random formulation so that they coevolve. The SGC model provides a new way of looking at the urban spatial process. Its descriptive validity begs further deductive and empirical investigations, but the model serves as a starting point for much richer interpretations of the urban spatial process than can be depicted here. The simulation results indicate that different structures have different effects on the total net energy of the system. In particular, the relationship between problems and choice opportunities, reminiscent of constraints of institutions, dominates the outcomes, whereas the effects of spatial, solution, and decision structures are insignificant. One would expect that the spatial structure, highly correlated to the physical environment, matters in the system, but the simulation results suggest that it does not. This counterintuitive finding may prompt a reconsideration of the extent to which the physical environment can improve human conditions, and to which the institutional structures can be helpful.

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