THE STUDY ON EXTENDED CELLULAR AUTOMATA BASED ON RELATIONAL DATABASE AND SPATIO-TEMPORAL SIMULATION

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ABSTRACT:

This paper present a development of the extended Cellular Automata (CA), based on relational database (RDB), to model dynamic interactions among spatial objects. The integration of Geographical Information System (GIS) and CA has the great advantage of simulating geographical process. But standard CA has some restriction in cellular shape and neighbourhood and neighbour rules, which restrict the CA's ability to simulate complex real world. This paper discuss cell's spatial relation based on spatial object's geometrical and non-geometrical characteristic, and extend cell's neighbour definition, and consider cell's neighbour lies in the forms of not only spatial adjacency but also attribute correlation. Then this paper put forward that cell's spatial relation between two different cells can be divided three type including spatial adjacency, neighbourhood and complicated separation. It is impossible to settle CA's restriction completely based on traditional idea, RDB-based CA is an academic experiment, in which some fields are design to describe the essential information needed to define and select cell's neighbour. The culture innovation diffusion system has multiplicate forms of space diffusion and inherited character, the RDB-based CA is capable of simulating more effectively. Finally this paper makes a case study on fashionable dress's diffusion, and acquired satisfied experimental result. Compared to the original CA, the RDB-based CA is a more natural and efficient representation of human knowledge over space, and is an effective tool in simulating complex system with multiplicate forms of spatial diffusion.

1. INTRODUCTION

The functionality of spatio-temporal analysis and modelling is a drive for GIS to further applications in various applied fields and digital earth plan. However Current commercial GIS lack those capabilities for saptio-temporal distribution, prediction, and simulation of spatio-temporal processes, and especially are inability to simulate complex dynamic interactions among economic, human, cultural and ecological processes (ZHANG & CUI,2000) . Thus there is an urgent requirement for traditional GIS to provide not only spatio-temporal data management services but also tools for scenario generation. The basic thought to study complexity spatial system is applying the theory of complex system, combining geographical essential rule, selecting proper study methods, and designing proper model. So more effective and powerful methods studying complex system begins to be applied to cognise geographic system one after another. For example, system dynamics, neural network, artificial intelligence, and etc(ZHOU etal.1999) . The integration of GIS and dynamical model has become a important research field of current GIS because it will improve greatly the GIS's ability of spatial decision support and simulation to geographical process, and the fundamental problem is that the conceptual representation of space and time in dynamic modelling and in GIS are not compatible(Takeyama & Couclelis, 1997). CA with the ability to calculate time and space are a potential solution to the incompatibility between GIS and dynamic models, so it has been noticed by more and more scholars and become an active advanced research field in complexity science. The standard CA has mature idea and arithmetic in studying cells and lattice based on geometrical characteristic, but it's impossible to simulate complex system with multiplicate spatial diffused forms. For example, culture innovation diffusion, enterprise spatial diffusion, martial invades and etc. The main reason is that object's spatial relation is based on geometrical characteristic in standard CA, but there are many spatial relationships based on non-geometrical characteristic in real world. The paper will extend standard CA model, discuss the possibility and flow of RDB-based CA, construct culture innovation diffusion's CA model based on relational database, and make a typical case study on fashionable dress's diffusion.

2. CELLULAR AUTOMATA AND ITS LIMITATION

Cellular automaton models are discrete-time system models with spatial extension. The abilities of cellular automaton to model the complex order hidden in spatial detail have been demonstrated. The basic form of the model consists of cells, states, neighbourhoods and transition rules. The states of the cells undergo iterative changes according to transition rules. Transition rules are functions of the cell's state and the state of neighbouring cells. The spatial behaviour of the process and the spatial interactions among spatial processes can be expressed by transitional rules. CA's main advantages in geographical and environmental modelling lie in three aspects. Firstly, CA combine with the spatial information stored in GIS easily, moreover remote sense data and other image data both can serve as CA's data source. Secondly, CA is capable of generating very complex, global spatial patterns by using simple, local transition rules, CA produce a fractal structure, which is a natural representation of a hierarchy between local and global behaviour(SHI & Pang,2000). Finally, CA has some characteristic including the bottom-to-top spatio-temporal modelling thought, strongly complicated calculation function, highly dynamical quality, etc(Batty & Couclelis, 1997).

However standard CA has some restrictions in cellular shape, neighbourhood and neighbour rules, which restrict the CA's ability to model complex real world. The main reason is that object's spatial relations are based on geometrical characteristic in standard CA. For example, according to standard CA, the cell's neighbor in one dimension often is gained within the distance of a cellular, the cell in two dimensions often is divided by regular spatial cell such as grid and equilateral triangle, and cell's neighbors are gained by some rules such as Von.Neumann, Moore and Margolus, etc. This directly cause cellular transition rule generally not to be applied to more distant cell. But in real world geographical and environmental system show more complicated characteristic of irregular, feedback, self-resemble, etc, and more spatial relations are represented through non-geometrical characteristic. For instance, it is uncertainty that religion and culture diffuse along the circumjacent cultural areas, and artistic action or fashionable dress incline to diffuse between the same level or sort cities. Therefore studying cell's spatial relation and extending cellular neighborhood definition is very necessary.

3. CELL'S SPATIAL RELATION AND CELL'S NEIGHBOR DESCRIPTION

CA is capable of studying the complexity of global spatial patterns based on the spatial interactions of local unit. In fact, local spatial relation is hidden in neighbour and transition rule and CA model iterative results represent whole spatial relation. So in some sense spatial relation and spatial conception are CA's unique advantage as dynamic model. Spatial relation can be established not only by spatial object's geometrical characteristic such as position and shape, but also by spatial object's geometrical together with non-geometrical characteristic including attribute of measurement, name, scale, etc, which result in statistical correlativity of spatial objects, spatial self- correlativity, spatial interaction, spatial dependent, etc(WANG etal., 1998). According to CA's theory all neighbours of a cell should be the aggregation of some cells that are capable of affecting the cell's next state. Therefore, for simulating complex real world more effectively cell's spatial relation is needed to consider not only spatial object's geometrical characteristic but also non-geometrical characteristic. Furthermore, we can extend cell's neighbour definition, and consider cell's neighbour lies in the forms of not only spatial adjacency but also attribute correlation. To model CA easily the paper put forward that cell's spatial relation between two different cells can be divided three type including spatial adjacency, neighbourhood and complicated separation. It is defined as cell's spatial adjacency relation that the distance between two different cells is 0 or less than some numerical value. It is defined as cell's spatial neighbourhood relation that the distance between two different cells is bigger than 0 or some numerical value. All the spatial relation between two cells except spatial adjacency and spatial neighbourhood are defined as complicated separation relation. For example, as shown in the figure 1, relation between Point object (I) and area object (II) is spatial neighbourhood, relation between area object (II) and line object (III) is spatial neighbourhood, relation between point object (I) and line object (III) is complicated desperation. In real world it is not certain that neighbouring geographical objects have interaction, it is not certain that the geographical objects that have interaction is adjacency, and it is not certain that the geographical objects with special studying aim mapped continuous geometry graph. So though standard CA has come to the top in simulating spatio-temporal system based on spatial adjacency relation, but because its theoretic basis is based on geometrical adjacency and don't make thoroughly analysis on cell's neighbourhood relation and complicated desperation relation, which restrict standard CA's ability to model complex real world. So we must extend standard CA to settle two problems: (1) the description on spatial neighbourhood relation; (2) the description on cell's complicated desperation relation.

Spatial adjacency relation describes distance and relative position relation between cell's neighbours, because the study on topology relation of spatial database mainly including spatial adjacency relation has come to the top, the basic thought is transforming spatial neighbourhood to spatial adjacency by dividing space, and then constructing information's table that can be queried. Some scholars divide the space area of researching objects by Voronoi map, which is able to transform some nonadjacent geographical objects to spatial adjacent relation. Voronoi map is effective tool that construct the relation because it has the ability of dividing spatial object effectively. As shown in the figure 1, the spatial adjacency between point object (I) and area object (II) has been transformed to spatial neighbourhood between area object (ABH) and area object (HBCFG), the relation between area object (II) and line object (III) has been transformed to spatial neighbourhood between area object (HBCFG) and area object (CDEF). Generally Voronoi map is transformed to Delaunay triangle net in most research article because the voronoi map of line object and area object is complicated.

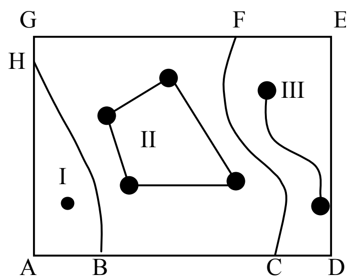

Figure 1. Neighbour cell's spatial relation transition from neighbourhood to adjacent

The description of complicated separated relationship is more complicated. As shown in figure 1, there are spatial interactions unable to be described by adjacency and neighbourhood relationship between point object (I) and area object (II) and line object (III). Firstly, the state of area object (II) don't affect the next state of point object (I), but the state of line object (III) affect the next state of point object (I). So point object (I) and line object (III) should become neighbour, but area object (II) and point object (I) shouldn't become neighbour. Secondly, both area object (II) and line object (III) affect the next state of point I, so both area object (II) and line object (III) should become point object (I)'s neighbour. It is impossible to solve some complicated nonadjacent spatial relation by the idea of Voronoi map. So we must design a new idea. Extension to CA based on RDB is an academic experiment, in which some fields are design to describe the essential information needed to define and select cell's neighbour.

4. CA'S CONCEPTUAL MODEL BASED ON RELATIONAL DATABASE

4.1 Cellular Attributes Datasheet in CA's Model Based on RDB

Two principles should be considered in modelling CA: (1) the integration and compatibility principle. CA should have the ability of integration with GIS and the compatibility with spatial database; (2) the reality principle. We should make cellular shape, neighbour rule and transition rule consistent with real world. The basic idea of CA based on RDB is that object's spatial relationship is reflected by cellular spatial relationship, and we consider not only object's geometrical characteristic but also non-geometrical characteristic, and defining and selecting cell's neighbour based on relational database, in which some fields are design to describe the basic information needed to define cell's neighbour. Some basic fields are necessary. As shows in table 1, the first is the field "CellID" which is used to describe cellular coding. The second is the field "Position" which is used to describe cellular position. The third is the field "CellularState" which is used to describe cellular state's value. The forth is the field "NeighborInformation" which is used to describe the cellular neighbor qualification often including level, sort, characteristic, etc. The fifth is the field "BelongCell" which is used to describe those cells whose neighbor is the current cell. The sixth is the field "IncludeCell" which is used to describe those cells who is the current cell's neighbor. The last is the field "NeighborNumber" which is used to describe the number of the cell's neighbour.

Name	Description
SysID	Objective identifier in system
UserID	Cellular coding
Position	Cellular position
CellularState	Numerical value of cellular state
NeighborInformation	Some basic information relevant with cell's neighbor definition. for example, grade, sort, scale, etc.
BelongCellular	Describe some cells whose neighbors include the currant cell.
IncludeCellular	Describe some cells whose neighbors belong to the currant cell.
CellularNumber	Number of cellular neighbor

Table 1. The cellular attribute datasheet in CA's model based on RDB

4.2 Flow Chart of Extended CA Based on RDB

As shown in figure 2, the flow chart of extended CA based on RDB includes five steps. The first is initialization. Object's area and cellular lattice is established according to studying purpose, object's information relevant to studying purpose is saved in GIS, object's database structure is updated automatically, records are added in cellular attribute table, and object's attribute is inherited by cell's attribute. The second is defining cell's neighbour rule and preparing for data. The rule to select cell's neighbour will be established according to whether affect cellular next state or not. Then some data item are confirmed according to neighbor selective rule and taken out from GIS's database and amended, and inputted as the field's "NeighborInformation" value. It can be applied to spatial analysis and query neighbor, and prepared to construct cellular neighbor relationship. The third is querying cell's neighbor and establishing spatial relationship. At first, data processing for the "NeighborInformation" item is performed in the basis of neighbor rule according to some ways and means such as buffer analysis, spatial statistical analysis, clustering analysis, etc. Then cell's neighbors are identified, the field "IncludeCellular" and the field "BelongCellular" are evaluated. Finally, cell's spatial relationship is established. The forth is calculating according to transition rule. Transition rule is established, the numerical value of cell's next state is calculated according to transition rule, the field "CellularState" is evaluated. The fifth is dynamically updating transition rule. It is necessary because dynamic cell's transition rule is more effective in the real world.

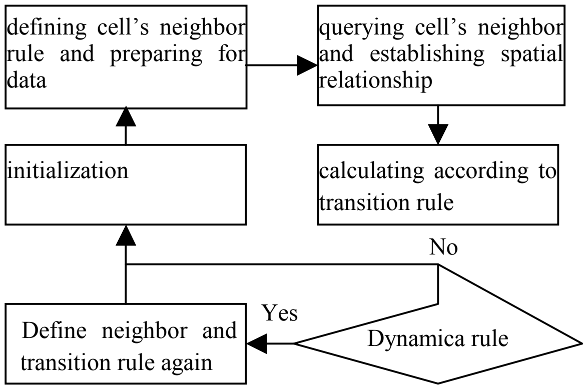

Figure 2. The flow chart of extended CA based on RDB

5. CASE STUDIES ON SPATIO-TEMPORAL SIMULATION

The extended CA based RDB is an effective tool in simulating complex system with multi-forms of spatial diffusion, and culture innovation diffusion has a great deal of forms of space diffusion and inherited character. So it is selected to serve as studying object.

5.1 Influencing Factors and Spatial Forms of Culture Innovation Diffusion

Culture innovation diffusion's essence is the spreading and diffusion of culture innovation information based on time and space, or is it's physical form's diffusion in spatio-temporal dimension, whose internal drive is the gravitation generated by difference between area objects and the culture organism's demand to survive(SHAN & BAO, 1996). Culture innovation diffusion's influencing factors mainly include culture innovation's potential energy "v", spatial distance "r", space diffusion's friction "mc" and culture inertia "yc". The mathematical expression of culture innovation diffusion's influencing factors is defined as:

$$S=f(yc, r, v, mc) \quad (1)$$

Where s is the culture innovation numerical value that a region received from another region, v is the gravitation between different areas which is decided by the discrepancy degree between different culture areas having discrepancy in resource, environment, convention and history, etc. Where r is spatial distance to which s is in inverse proportion because of friction and information's loss in culture diffusion. Where mc is the spatial friction including all kinds of resistances generated by terrain, polity, military affairs, religion, etc. Spatial friction not only baffles but also distorts culture information's diffusion. Coefficient of Spatial friction can be design to measure some factors' baffling function, and its value is from 0 to 1(SHAN & BAO, 1996). Where yc is culture inertia which means that traditional morality, religion and jural notion is general rootedness, and always has the tendency of inheriting traditional things.

Based on current studying production according to geomitrical relationship, probability and seletion the paper put forword that culture spatial diffusion has five basic form, which include adjacency diffusion, adajacency probability diffusion, adajacency selection diffusion, non-adajacency selection diffusion and non-adajacency probability diffusion. Adjacency diffusion means that culture innovation would diffuse in condition that spatial adjacency relationship exists without regard to grade and sort. Adajacency probability diffusion means that culture innovation diffuse by probability in despite of adajacecncy relationship. Adajacency selection diffusion means that culture innovation diffuse selectively in despite of adajacency relationship. Non-adajacency selection diffusion means that culture innovation diffuse selectively in despite of non-adajacency relationship. Non-adajacency probability diffusion means that culture innovation diffuse by probability in despite of non-adajacency relationship. In general, non-adajacency diffusion has the discrete and inlaid feature in spatial shape, and probability diffusion based on haphazard is irregular in spatial shape.

5.2 Modelling Culture Diffusion System Based on CA

Equation (1) describes the interaction between two objects. In fact one culture object area is often affected by numbers of culture object areas in real world. So based on equation (1) the innovation diffusion's accumulative value that describe one culture object area receive from other object areas can be calculated as:

$$G=\Sigma S_i=\Sigma f(yc, r_i, v_i, mc_i) \quad (i=1,2,\ldots\ldots N) \tag{2}$$

Where G is the innovation diffusion's accumulative value, N is the number of cell's neighbor, yc is relevant to cell's historical state, r_i, v_i, and mc_i is relevant to other object area's actual states. So equation (2) can be transformed as:

$$S_t=f_1(S_{t-1}, \Sigma f_2(r_i, v_i, mc_i))=f_3(S_{t-1}, O_1, O_2, \ldots O_i, \ldots O_N) \quad (i=1,2,\ldots\ldots N) \tag{3}$$

Where S_t is the cell's current state, S_{t-1} is the cell's previous state, f_1, f_2 and f_3 are functions, O_i is the state of diffused source i that affect the current cell's state. Equation (3) is a normal descriptive form of cell state's transition rule. Therefore the conceptual model described by equation (2) can also be described by cellular automata model as:

$$S_t=S_{t-1}+\Sigma H_i \quad (i=1,2,\ldots\ldots N) \tag{4}$$

Where H_i is the instantaneous value that the neighbor cell i cause. It is difficult to model culture diffusion based on CA because of geographical spatial non-homogeneous character. To calculate easily, the diffusion from culture innovation source cell to culture acceptant cell can be divided two steps: (1) culture innovation diffusion obeys the same diffused equation in every direction; (2) culture acceptant cell receive culture innovation through the function of spatial friction.

Suppose a culture cell's diffusion has probability, then large numbers of cell's diffusions is a probable process, and the process is a continuous MarKov process that obeys KerMoglov diffused equation. Innovation diffused accumulative value accord with Logical curve because Torsten Hagerstrand has proved that diffused velocity accord with normal school curve with temporal change. Therefore culture innovation's dynamic diffused equation based on non-homogeneous space is obtained as(GUO, 2001):

$$C(r,z)=\begin{cases} C_{max}.\mathrm{erfc}\{[r-\rho(z)]/[4\sigma(z)]^{1/2}\} & r\geqslant\rho(z) \\ C_{max}.\mathrm{erfc}\{[\rho(z)-r]/[4\sigma(z)]^{1/2}\} & r<\rho(z) \end{cases} \tag{5}$$

$$D(r,z,\Delta t)=C(r,z)/[1+a.e^{-k.\Delta t.C(r,z)}] \tag{6}$$

$$\Delta t=t-t_0 \tag{7}$$

$$z=m_0-m \tag{8}$$

Where C(r,z) is the saturated value of culture innovation that culture acceptant cell has received from the culture source cell, $D(r,z,\Delta t)$ is the instantaneous value of culture innovation that culture acceptant cell has received from culture source cell in the time t, Δt is the time difference between t and t_0, a and k is coefficients relevant to diffused time and diffused velocity, r is the distance between culture source cell and culture acceptant cell, m is general culture level of culture acceptant cell, m_0 is general culture level of culture source cell, C_{max} is culture innovation value of source cell; erfc（x）is Gauss function; ρ(z) is the coefficient function of diffused offset; σ(z) is the diffused coefficient function. The mathematical expression between H and $D(r,z,\Delta t)$ is defined as:

$$H=mc\times D(r, z, \Delta t) \tag{9}$$

$$H_i=mc_i\times D(r_i, z_i, \Delta t) \quad (i=1,2,\ldots\ldots N) \tag{10}$$

Where Mc is from 0 to 1. When culture source cell and acceptant cell are similar in economy, society, culture, etc and traffic condition between two cells is convenient, the numerical value of Mc is 1. By contraries , when the discrepancy between source cell and acceptant cell is very large and there is traffic jam between two cells, the numerical value of Mc is 0.

Therefore, to random culture source cell and acceptant cell, we could acquire the innovation diffused value H_i in condition that C_{max}, r, m, m_0 and mc are known and the function of ρ(z) and б(z) are established, random culture innovation cell's state value G can be calculated according to neighbour cell's defining qualification and cellular state's transition rule.

5.3 A Case Study on Fashionable Dress's Diffusion

Fashionable dress's diffusion is a typical process of culture innovation diffusion. Its diffused alleyway is affected by a great deal of factors including traffic, economy, polity, religion, climate, etc. The paper mainly discusses theory and method and don't involve in actual geographical area because of the difficulty in collecting data. Suppose that there is a studying region whose basic condition is defined as follows: (1)there are railroad and river (or lake) in studying region which is divided five sub regions including O, A, B, C and D, there is a city in every sub region, and there is a fashionable dress diffused source in sub region O; (2) there is railway in sub region B by which contact with sub region O, the economy and culture are similar in sub region B and O; (3) there is also railway contacting with sub region O in sub region D, economic condition is similar in sub region D and O, But there is large difference in culture and convention between sub region D and O because of river's obstruct; (4) there isn't railway contacting with sub region O and the level of economy and traffic is low in sub region A; (5)residents are stick-in-the-mud in sub region C. Cellular lattice is divided as 100×75 cells. Neighbour relationship is defined as follows: (1) there are neighbour relationships between all the cells that is belong to city area; (2) there are some developing cells similar to small town in real world in every sub region, there are neighbour relationships between developing cells and city cells; (3) ordinary cells select adjacency cells whose culture innovation level is higher as neighbour cell, and its diffusion obey probability. The cellular diffused rule is defined as follows: (1) the probability of adjacency diffusion and adajacency probability diffusion is both 50%; (2) the probability, direction and distance of non-adjacency diffusion are established according to traffic and economic condition in attribute table. The innovation value of diffused source is defined as 100. According to general fashionable dress's diffused rule diffused equation can be simulated by C(r, z) = 100erfc[r(2.44+0.329z)]. Spatial frictional can be obtained by economic field multiplied by traffic field in attribute table. As shown in the figure 3 and figure 4, simulating result that are capable of showing fashionable dress's diffused process is acquired after the fiftieth calculation through CA program. Figure 3 is the diagram of experimental region's first state. Figure 4 is the diagram of cellular state based on fifty calculations. The basic character of fashionable dress's diffusion is show clearly by experimental result as follows: (1) diffused system has some rule and character of uncertainty; (2) diffusion has the character of diffusing firstly between the same grade and attenuation with distance; (3) adjacency diffusion is main diffused form in sub region; (4) traffic and river have great selective role in the process of diffusion; (5) mutual diffusion is not clear in sub region's boundary.

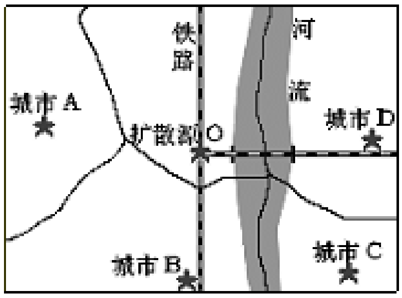

Figure 3. The diagram of experimental region's first state

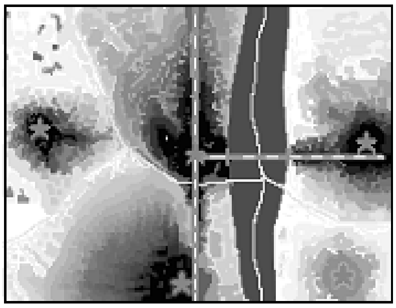

Figure 4. The diagram of cellular state based on fifty calculation

6. CONCLUSION

CA is simple in principle, wide in potential applications, hierarchical in nature and so they are powerful in theory. However the restrictions of standard CA limit their ability to model the complex real world. It is impossible that solve the CA's restriction by extending CA model through traditional idea. Current standard CA defining neighbour cell is mainly based on geometrical character, in fact there are a great deal of spatial relationships based on non-geometrical character in real world. For example, enterprise's spatial diffusion, national economic aid crossing region, pop's diffusion, and etc. So cell's spatial relation is needed to consider not only spatial object's geometrical characteristic but also non-geometrical characteristic. Furthermore, we can extend cell's neighbour definition, and consider cell's neighbour lies in the forms of not only spatial adjacency but also attribute correlation. Extending cell's neighbour definition based on RDB not only can simulate interaction among cells that are adjacency each other but also can simulate interaction among cells that are non-adjacency each other, not only provide more natural manner to describe human knowledge but also provide more effective tool to simulate complex real world. Culture innovation diffused system has some rules and has complex system's uncertain character. A case study on fashionable dress's spatial diffusion process show that cultural diffusion follows some rule and has some uncertain characteristic of complicated system, and culture innovation diffuse firstly between the same grade cell and attenuation with distance, and transportation, river, terrain and convention etc have a great selective role in the process of diffusion. The result of case studying consists with academic forecast. Therefore studying extended CA based on RDB not only has the academic value but also has great potential ability in application. CA has the advantage of simulating complex system with multiplicate forms of space diffusion. Compared to the original CA, the RDB-based CA is a more natural and efficient representation of human knowledge over space. But the extended CA based on attribute's RDB still has some problems needed to lucubrate. For example, how to solve the problem of tremendous data saving cellular record, and how to search for neighbour, design proper transition rule, and so on. These problem's analyses and study will urge the GIS integrated with CA to improve the level of decision support and the ability of simulating complex real world.

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