CELLULAR AUTOMATA IN URBAN PLANNING AND DEVELOPMENT

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ABSTRAK

Urban planning is a complex process as urban system is the resultant of interactions between its subsystems. Knowing future projection of physical urban development can play a vital role in successful urban planning and development. Therefore, it is important to have a good understanding of the interactions between urban system components to correctly predict future urban growth. This paper proposes the Celullar Automata (CA) model to predict the future of urban development. Due to shortcomings of traditional modeling methods which are generally static, linear and are based on simple systems theory, it is expected that the proposed CA model which is dynamic and nonlinear will provide better understanding of the urban system and provide better prediction of urban growth.

Keywords: *urban planning and development, cellular automata (CA), transition rules, neighborhood effects*

INTRODUCTION

Urban planning procedure is a catch-all title that can be used to present a new wave of research in urban studies. Knowing the future projection of physical urban development based on land use state and transportation network situation can play a vital role in urban planning. Nonetheless, precise prediction or simulation of that future state is not simple as there are too many factors with different intensities such as population, residents, retail and services, infrastructural, industrial, and environmental affairs etc. that must be considered.

During last decade, many attempts using variety of techniques were made to predict and simulate how cities will be developed in a distinct future; some of these techniques are Economic principles, Statistical analysis, spatial interaction, and Cellular Automata. These all techniques are used to predict and simulate cities development but the output of each of them are necessary coincident on each other. Therefore try to develop the precise of such mentioned techniques to produce the best predictor and simulator cities development model is important.

PREDICTORS AND SIMULATOR TECHNIQUES

Some of most important and familiar techniques which are used to predict and simulate how cities will be developed in a distinct future are as below:

A. *Economic Principles*

This technique focuses on the relationship between urban land use and the value of urban land. This leads to a simple model with decreasing land prices as you move away from city centre regarding the accessibility via existed transportation system. The land use resulting from these assumptions is that of a typical monocentric city. The focus on land in economic theories has changed over time. The well-known theories of Ricardo and Von Thunen have laid the foundation of land price and land use theories. Ricardo (1817, in Kruijt et al., 1990) explained land prices in terms of land quality. The renewed interest for geography in economics (e.g. Krugman, 1999) offers interesting concepts to analyse the spatial interaction between actors in terms of centripetal forces leading to concentration, and centrifugal forces leading to spatial spread of functions (Eric Koomen et al., 2008).

B. *Statistical Analysis*

Static (or cross-sectional) models directly calculate the situation at a given point in time; many examples exist of models that rely solely on a statistical description of observed past land use changes to simulate future patterns (e.g. Schneider and Pontius, 2001; Serneels and Lambin, 2001). These empirical-statistical models have the advantage of being relatively easy to construct, but they miss a theoretical foundation as no attempts is made to understand and simulate the processes that actually drive land use change. Therefore, the applicability of these purely statistical models is limited. They can be used to simulate possible spatial developments within a relatively short time-span under “business as usual “conditions, but for example they are not suited to simulate possible changes according to diverging socioeconomic future scenarios(Eric Koomen et al., 2008).

C. *Spatial Interaction*

A classical group of land use models is based on spatial interaction modelling theory. Spatial interaction in a social, geographical context refers to every movement in a space as a consequence of a human process (Haynes and Fotheringhamn, 1984). One of the first researchers to model the interdependence of these systems was Putman (1983) and one of the newest one is Timmermans (2003). A related type of research focuses on the interaction between land use and transport. Central to this approach is the assumption that land use is influenced by the available infrastructure network and vice versa; the transportation demand depends on the spatial configuration of the different, mostly urban, land use types. But these kinds of models can be so complicated which needs to become simpler. (Eric Koomen et al., 2008).

D. *Cellular Automata*

The cellular automata (CA) methods deriving from mathematics are very well suited for imitating complex spatial process on the basis of simple decision rules (Wolfarm, 1984). To simplify the complexity in spatial interaction models a grid of cells are employed. Every cell has a certain state (or function) that is influenced by its surrounding cells as well as the characteristics of the cell itself. The degree and direction of interaction between the functions is determined through so-called transition rules. A strong dimension of this approach is the simulation of the interaction of a location with its direct surroundings that has empirically proven to be an important driver of land use change (O’Sullivan and Torrens, 2000; Verburg et al., 2004).

MATERIAL AND METHODS

The modern technique which is surveyed in this paper refers to Cellular Automata (CA); CA include such dynamic systems that are incoherent in terms of time and space (Chenghu and Zhanli, 1999). CA was first proposed as a framework to explore the logic of life by Von Neumann and Stanislaw Ulam in the 1940s (Rucker, 1999). Cellular Automata consists five main parts - Lattice, Cell state, Neighbourhood, Transition rules, and time.

Lattice

Lattice is the space that CA exists and evolve. Lattice is primarily one-dimensional, but in the Automata that are designed for geographic purposes such as urban CA modelling, it is normally defined in two-dimensional space. Generally, CA is created in a regular lattice such as square or other regular polygons including triangle and octagon (Torrens, 2000). Nonetheless, in some urban fields, irregular lattices have also been used (O'Sullivan, 2002).

Cell State

The cell state is the status, which each cell can take in the CA iteration process where different cells take some status to represent the final result of simulation. In most CA models, cells only take a Boolean cell state, 0 or 1. However, researchers can use other cells' states depending on their needs (e.g. Neumann in his Cellular Automata has presented 29 cell states).

Neighbourhood

The neighbourhood shows the location of each cell within a group of cells. Generally, a neighbourhood consists of an examined cell itself and any number of cells in a given configuration around the examined cell (Torrens, 2000). Each cell state can be changed as the result of the cell interaction with its neighbourhood under the transition rules. Also different CA models use different neighbourhood sizes and configurations. The most famous neighborhoods in a two-dimensional CA neighbourhood models of Moore, Conway, and Neumann (Figure 1). The Moore's neighbourhood includes nine cells located in a 3×3 grid, and the exam cell in the centre. The Neumann's neighbourhood includes five cells and the exam cell located in the centre and other cells those are in its neighbourhood had one common side.

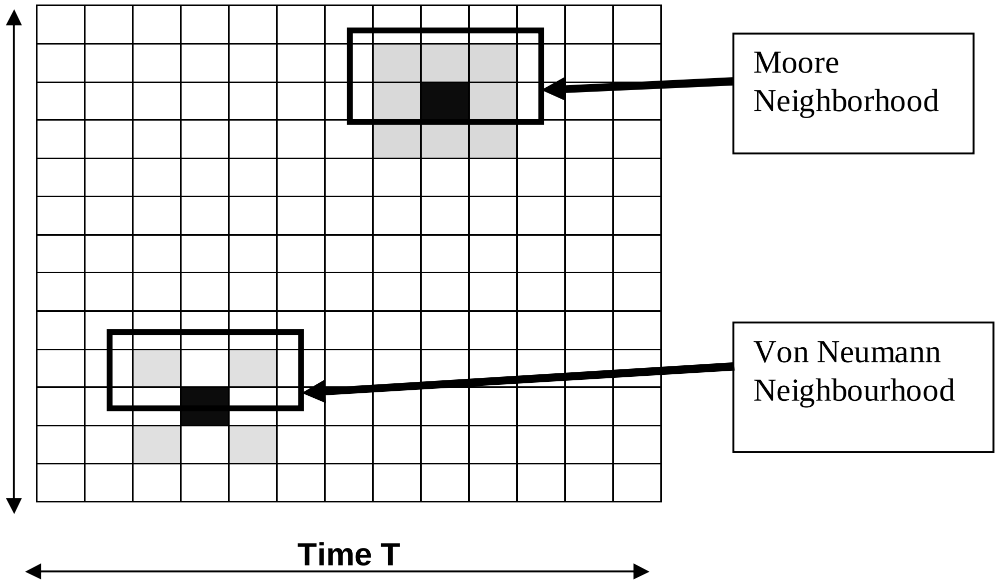

Figure no 1 variety Cellular Automata neighbourhood

Transition Rules

Transition rules are the engines of change in CA models and specify the behaviour of cells between time-step evolutions, deciding the future states of cells. Transition rules in basic CA are being used unanimously and simultaneously for all cells. These rules are generally formulated as IF, THEN, and ELSE statements that rely on input from a neighbourhood template to evaluate their results. Actually, the transition rules replace traditional mathematical functions in models (Batty, 1997). The merits of this methodological trend is that these rules show how real systems work, as well as simplifying complex system to plain details while including dynamic states of original system.

Time.

Time in CA models is discrete and the length of the periods and distances between time-steps can be defined differently in different CA models. Whenever the distance between time-steps were longer, the transitions in CA would be more discrete and inverse. The cells have different states in two time-steps (T, $T + 1$) and naturally the CA would be changed during the period from T till $T + 1$. Therefore CA modelling can simulate the dynamic systems via figured templates during the transition from T to $T + 1$. Because almost all urban CA models originated from two dimensional models, these kinds of models are described in next step.

RESULTS AND DISCUSSION

The most used kind of CA to predict and simulate the cities development refers to Two Dimensional (2-D) Cellular Automata; (2-D) Cellular Automata models refer to those CA that their neighbourhood and lattice are defined in two dimensional plates (Figure 3-1). In this figure, a 13×13 grid cells, filled or unfilled cell state, Moore and Neumann neighbourhoods including respectively 9 and 5 cells, time (T and $T + 1$) in a two dimensional CA are shown and finally the different transition rules can give out different results. Therefore, it is obvious that transition rules are the core part of the five CA elements above.

The evolution of cells takes place from T to $T + 1$. So, the cell state in $T + 1$ is determined via transition rules based on its state in T and its neighbourhood situation. This process in a two dimensional CA model can be mathematically expressed as:

$$\mathbf{ST+1 = f\ (St,\ \Omega t,\ T)} \qquad \text{(equation no1)}$$

St+1 is the exam cell’s state at time t+1,

St is the cell’s state at time t,

Ωt is the cell’s neighbourhood situation at time t.

T denotes the transition rules of the CA.

Using this formula, it is possible to find the situation of whole cells after each CA interaction. This formula is the core part of CA and it articulates the CA’s evolution process clearly.

Transition Rules in Cellular Automata

As it mentioned before transition rules are engines of changes in CA models. They determine the cells behaviour during the transition in different time-steps, so the cell states would be determined by them. Transition rules in a mere CA are applied homogenously and simultaneously for all cells (Torrens, 2000).

Michele Batty proved that mentioned mere CA transition rules can be formulated via "**If**, **Then**, **Else**" and figure the cell state changes based on different inputs of neighbourhood templates. For example one kind of typical transition rules in cellular automata can take the following form:

If something happens in the neighbourhood of a cell,
Then some other thing will happen to the cell.

For example in a famous CA model on "game of life" that was devised by the British mathematician John Horton Conway in 1970, one of the transition rules is formulated as below:

If the cell state in the time (*T*) is "dead"
    If the cell state in the time (T) is "dead"
    And If there is more than three "alive" cells in its neighbourhood
    Then the cell state in time (T+1) change to "alive"

As is seen in above process, a Cellular Automata transition rule can be determined based on neighbourhood effects and without considering the other effects. These kinds of transition rules can be integrated and mathematically shown as:
TPt+1 = f (St, NB) (equation no 2)

TPt+1 = transition potential of tested cell at time t+1,

St = tested cell state at time t,

NB = the neighbourhood effect.

In Eq. (1), the transition potential of tested cell at time $T + 1$ is determined via tested cell state and its neighbourhood effect. Therefore, transition potential of a distinct tested cell is not only affected by its neighbourhood, but also by other parameters such as accessibility, suitability, and transportation factors that affect it (e.g. usage of inverse distance function to apply the accessibility effect). Hence, the transition potential of each cell can be calculated as below:

TPt+1 = f (St, NB, AC, SU, TPE… (equation no 3)

TPt+1 = transition potential of tested cell at time t+1,

St = tested cell state at time t,

NB = the neighbourhood effect,

AC = accessibility effect,

SU = suitability effect

TPE = transportation effects

Thus, the application of the urban CA model to simulate the land use results in the changes of cell's state due to different transition potential rules. Also even the details of two transition rules were the same, the results may not necessarily be the same. For example, in the case of simulating the changes of two types of land uses (e.g. residential and commercial), both under the effects of neighbourhood and suitability, because of different destinations they may get different importance coefficients and the transition rules would be different. Therefore, land use simulation via CA models is completely dependent upon the destination. Thus, Eq. (3) can expressed more comprehensively as below:

TPdst+1 = f (St, NB, AC, SU, TPE…) (equation no 4)

Where:
TPdst+1 = transition potential of tested cell at time t+1 regarding the destination of simulation

Besides, based on Eq. (4), the tested cell state before transition (St) affects its transition potential but does not affect the transition potential rules. So, the effect of tested cell state before transition can be considered as one of the suitability effects. For example, to calculate the transition potential of two tested cell with different primary states (e.g. residential and industrial) to change to commercial state, although their transition potential formulas are the same, but their transition potentials are different because of their different suitability to change to commercial land use. The relationship between primary tested cell state, final tested cell state, and transition potential rules can be shown as in Table 1 (Junfeng, 2003):

Table 1 relationship between primary cell state, final cell state and transition potential rules

Industrial	Commercial	Residential	primary tested cell state
Formula (3)	Formula (2)	Formula (1)	Residential
Formula (3)	Formula (2)	Formula (1)	Commercial
Formula (3)	Formula (2)	Formula (1)	Industrial

In Table 1, Formula (1), (2), (3) are the different transition potential rules to calculate the transition potential of different primary cell state in order to change to a determined final state. Thus, the number of transition potential rules in the model depends on the number of primary cell states.

In simulating land use changes using with CA, some other rules relating to incompatibility and conflict are being used too. For example, calculating the transition potential of one determined tested cell to change to variety of land uses give out different amounts. Therefore, to determine the future cell state based on these calculated amounts requires other rules. To explain more the different cell states in a distinct part of the grid are shown in below figure:

A	**B**
C	**D**

Figure5 different cell states in a distinct part of the grid

The amounts of transition potential for residential land use are as:

0.9	**0.8**
.7	**0.5**

The amounts of transition potential for industrial land use are as:

0.8	**0.9**
0.6	**0.6**

In this example, four cells (A, B, C, D) are surveyed. Calculation is done on two distinct states (residential and industrial). As default to accepting each of these lands uses two simulated cells, but regarding the above calculation the final state of four above cells still are vague. Therefore the confliction resolving rules are needed to fix this problem. If the modeller employs the “allocating to higher potential” rule, below states will be given for the four cells:

R	**I**
R	**I**

Figure 6 different cell states in allocating to higher potential rule
(R: Residential, I: Industrial)

As shown in Figure 6, because of higher amount of the transition potential of A and C cell states to change to residential land use rather than industrial land use, they are changed to R (residential land use) and also with the same justification the cell states of B and D are changed to I (industrial land use). However, if the modeler employs different confliction resolving rule, the results will be different. For instance with employing the “allocating to first amount” rule the result will be as below:

R	**R**
I	**I**

Figure7 different cell states in allocating to higher potential rule

Figure 7 shows that although the Industrial transition potential of cell B is higher than its residential transition potential, the cell state of B has been changed to residential state. This transition is because of the time precedence of first two amounts for residential land use rather than industrial land use. With the above example, now it is obvious that the final states of cells not only are based on transition potential amounts of the cells, but also depends on confliction resolving rules too. This relationship and dependence can be seen in the diagram below:

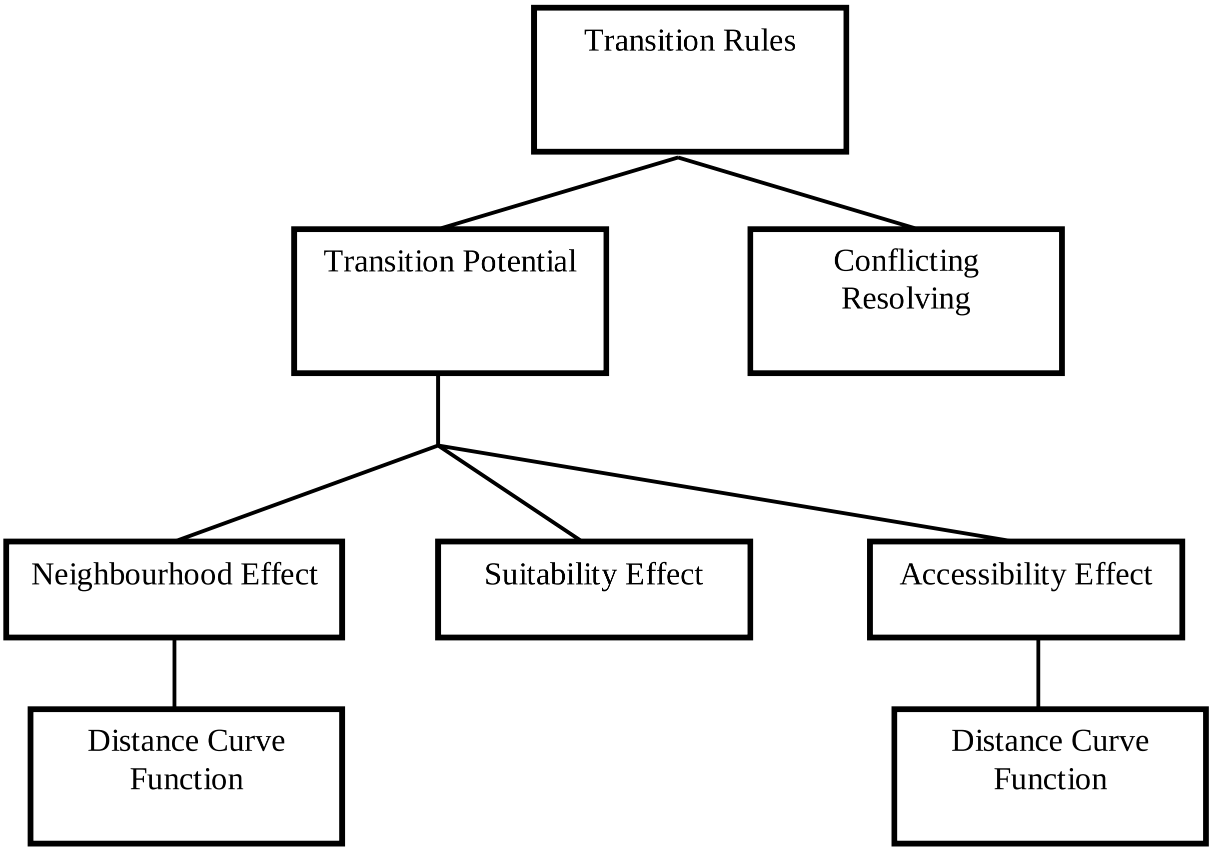

Figure no 8 Transition Rules diagram in CA models

According to Figure 8, transition rules have two main parts - “Transition Potential Rules” and “Confliction Resolution Rules”. The transition potential rules include some Sub-Rules such as neighbourhood effect, suitability effect, accessibility effect and they are defined via distance curve function.

Most of the land use CA models employ the “allocating to higher potential” rule as their Confliction Resolving Rules. Thus, cell state changes are directly related to its transition potential amounts rather than the land use precedence. In other word, each cell state changes to the land use with the highest amount of transition potential in the cell. Therefore, in these kinds of models, the transition rules are the same as transition potential rules and that is why most of the people think that these two kinds of rules are one rule.

There is an another way to resolve the conflictions; in which different weights are allocated to different land uses and then transition potential rules and confliction resolving rules are combined. Therefore the final formula of transition potential for last example is as below:

$$\mathbf{TP = (TPr \times WR) + (TPc \times WC) + (TPi \times WI)} \qquad \text{(equation no 5)}$$

Where:
TPr = transition potential to residential land use

TPc = transition potential to commercial land use
TPi = transition potential to industrial land use
W = the weight that is allocated to each land use by the modeller based

The Application Of 2-D Urban CA Models

One of the main usages of two dimensional (2-D) CA belongs to urban systems. When each of CA's elements is allocated to its distinct counterpart in urban system, the urban CA system would exist. For example, the lattice area can be defined to coincide with urban area, and also cell states can be determined according to different kinds of land uses (residential, commercial, etc.) Similarly, different transportation flow conditions in the routes (free, semi crowded, etc.), can be defined in simpler Boolean condition such as built and not built space. Also, it is possible to define the cell's size and its neighborhood's size and configuration proportionate to simulation accuracy and available data. Finally, in the most important stage, the transition rules can be determined according to defined urban system. Actually, the modelling process is the process of changing from one urban CA system to a different urban CA models through the application of transition rules.

Urban CA models have been employed to study the urban systems especially as a planning support system (PSS). As urban CA models are appropriate to produce different scenarios proportionate to determined criterions and restrictions; they can simulate different "what if" questions, thus making decision about policies and determining the direction of development will become easier. There are a lot of these kinds of urban CA models, e.g. the Island, ReMco, Wadbos, etc. models (Figure 3).

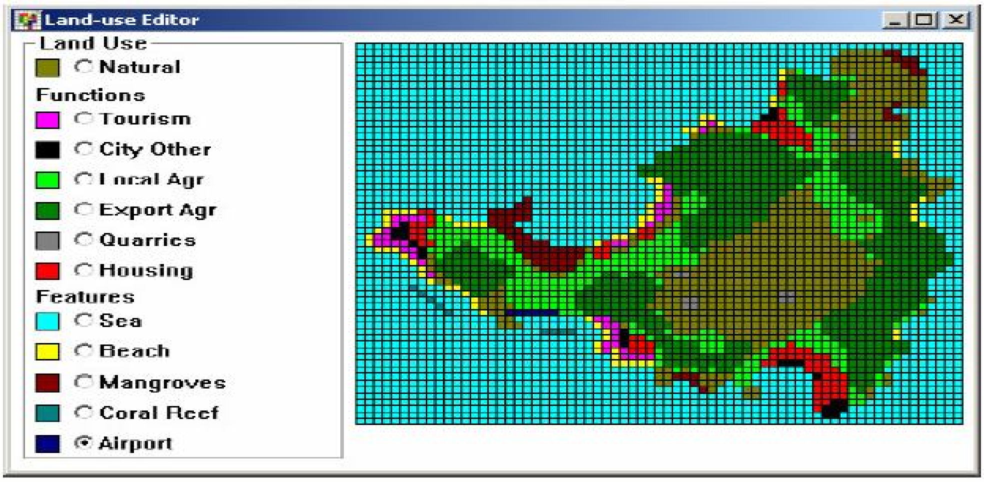

Figure 2 Primary state of Island model (before CA transition)

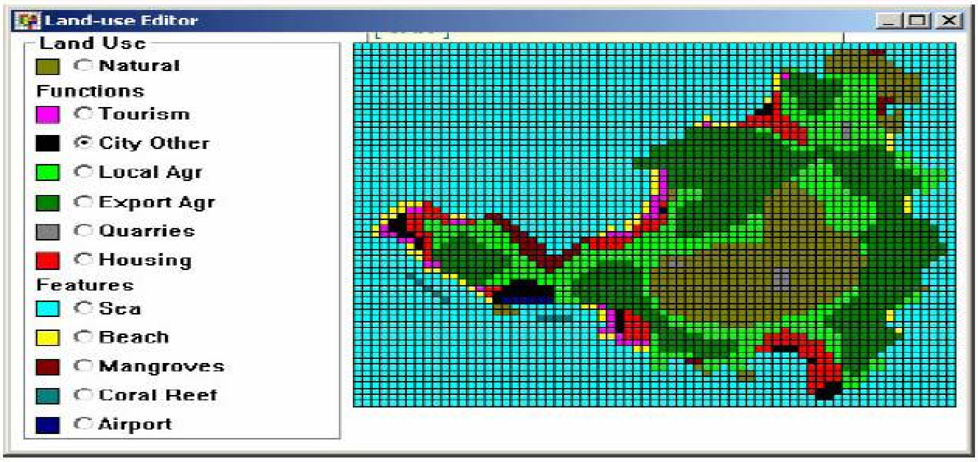

Figure 3 simulated state of Island model (after CA transition)

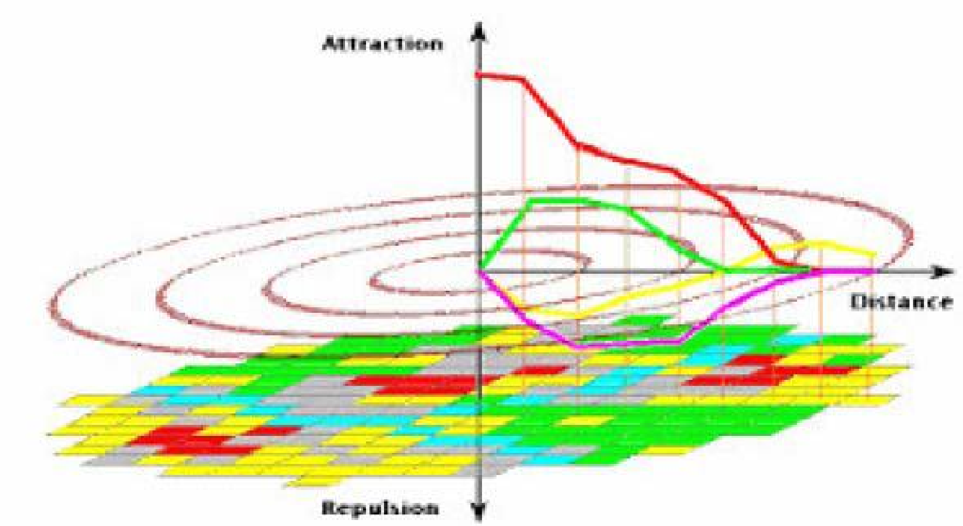

Figure 4 Defined criterion and effects of some neighbourhood in Island model

In the above figures, one square grid is proportionate to the district and simulated area as defined by the modeller. The cells are placed regularly in a square shape. Different kinds of land uses are presented via different cell states and are shown in different colours. Neighbourhood as it is shown in Figure (4) is defined in a big circular shape. Also, the modeller has employed different transition rules that some of them can be seen in above figure as different distances curve functions. This model just is one example of different kind of urban CA models, many of these are designed by urban modellers.

Totally Cellular Automata applications are numerous and various in different fields such as technology, ecology, humanities, economics, agricultural science, art, and especially in urban development which makes it as a popular method. Generally, CA are such systems that provide the possibility of surveying the world and its complex systems in a complete artificial environment. Therefore, complex physical and biological systems can be depicted via CA mathematical models and then understanding the CA results to understand the real complex systems.

Cellular automata can be known as plainest method to depict the dynamic systems, besides this method is a spatial method in essence. These two specialties (plainness and spatial) of CA have brought it up as desirable tool to modeling the dynamic of land uses.

CONCLUSION

To better understand urban development and growth mechanisms, authorities must comprehend related urban factors and processes with its subsystems, management and planning structure, and external environment. Urban system form is the resultant of interactions between its subsystems. For example, spatial form changes are the real interpretation of socio-economical changes. In other words, all the problems and changes in socio-economical processes can find their like in spatial form such as land use changes, spatial segregation, different congestions etc. Therefore, understanding the reasons and quality of spatial distribution of urban activities and their interactions quality is a vital subject for authorities. Besides, determining control policies and guiding the urban growth process is one of the main duties of urban authorities. Thus spatial analysis and development process and also complex and dynamic urban system evolution modelling can be employed as an appropriate support tool by planners to realize and interpret the urban development and growth mechanisms.

At the same time, the existence of various complex phenomena in contemporary cities, nonlinear and complex growth of these cities, development restrictions etc. have made the efforts towards this understanding more difficult. Unfortunately, comprehension of all these complex characteristics is out of traditional modelling capability since these models generally are static, linear and are based on simple systems theory (top-down and deductive). Therefore, exploring new methods to modelling of dynamic, nonlinear, and bottom-up systems is necessary.

Models for simulating future urban development exist in many different types and forms, but they all rely on a limited number of theories and methods such as Economic principle, spatial interaction, cellular automata, statistical analysis, optimization techniques, rule-based simulation, multi agent models, micro simulation.

Static (or cross-sectional) models directly calculate the situation at a given point in time, whereas dynamic models work with intermediate time-steps, each of which might become the starting-point for calculating the subsequent situation. Dynamic modelling, therefore, takes possible developments during the simulation period into account, providing a richer behaviour and the possibility to better mimic actual spatial development.

With Cellular Automata (CA), it is possible to manage an acceptable simulation and prediction processes with high degree of accuracy as many types of data can be inputted into the model representing different variables.

The CA model acts dynamically as much as possible as it can adapt to dynamic time and place in real world. Besides, the CA model can be applied with high degree of confidence level in different regions because it can convert various specific features – details, mechanisms, and behaviour – of each spatial unit into their proportional variables. In addition, it can cover temporal changes and transitions as a dynamic model for urban dynamic systems.

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