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Research Article

Modelling sustainable urban development by the integration of constrained cellular automata and GIS

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Abstract. Cellular Automata (CA) have attracted growing attention in urban simulation because their capability in spatial modelling is not fully developed in GIS. This paper discusses how cellular automata (CA) can be extended and integrated with GIS to help planners to search for better urban forms for sustainable development. The cellular automata model is built within a grid-GIS system to facilitate easy access to GIS databases for constructing the constraints. The essence of the model is that constraint space is used to regulate cellular space. Local, regional and global constraints play important roles in affecting modelling results. In addition, 'grey' cells are defined to represent the degrees or percentages of urban land development during the iterations of modelling for more accurate results. The model can be easily controlled by the parameter k using a power transformation function for calculating the constraint scores. It can be used as a useful planning tool to test the effects of different urban development scenarios.

1. Cellular automata and GIS for urban simulation

Cellular automata (CA) were developed by Ulam in the 1940s and soon used by Von Neumann to investigate the logical nature of self-reproducible systems (White and Engelen 1993). A CA system usually consists of four elements—cells, states, neighbourhoods and rules. Cells are the smallest units which must manifest some adjacency or proximity. The state of a cell can change according to transition rules which are defined in terms of neighbourhood functions. The notion of neighbourhood is central to the CA paradigm (Couclelis 1997), but the definition of neighbourhood is rather relaxed. CA are cell-based methods that can model two-dimensional space. Because of this underlying feature, it does not take long for geographers to apply CA to simulate land use change, urban development and other changes of geographical phenomena. CA have become especially, useful as a tool for modelling urban spatial dynamics and encouraging results have been documented (Deadman *et al.* 1993, Batty and Xie 1994a, Batty and Xie 1997, White and Engelen 1997). The advantages are that the future trajectory of urban morphology can be shown virtually during the simulation processes.

The rapid development of GIS helps to foster the application of CA in urban

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simulation. Some researches indicate that cell-based GIS may indeed serve as a useful tool for implementing cellular automata models for the purposes of geographical analysis (Itami 1994). Although current GIS are not designed for fast iterative computation, cellular automata can still be used by creating batch files that contain iterative command sequences. While linking cellular automata to GIS can overcome some of the limitations of current GIS (White and Engelen 1997), CA can benefit from the useful information provided by GIS in defining transition rules. The data realism requirement of CA can be best satisfied with the aid of GIS (Couclelis 1997). Space no longer needs to be uniform since the spatial difference equations can be easily developed in the context of GIS (Batty and Xie 1994b).

Most current GIS techniques have limitations in modelling changes in the landscape over time, but the integration of CA and GIS has demonstrated considerable potential (Itami 1988, Deadman *et al.* 1993). The limitations of contemporary GIS include its poor ability to handle dynamic spatial models, poor performance for many operations, and poor handling of the temporal dimension (Park and Wagner 1997). In coupling GIS with CA, CA can serves as an analytical engine to provide a flexible framework for the programming and running of dynamic spatial models.

2. Constrained CA for the planning of sustainable urban development

Interest in sustainable urban development has increased rapidly in recent years. Unfortunately, the concept of sustainable urban development is debatable because unique definitions and scopes do not exist (Haughton and Hunter 1994). However, this concept is very important to our society in dealing with its increasingly pressing resource and environmental problems. As more nations are implementing this concept in their development plans, it has created important impacts on national policies and urban planning. The concern over sustainable urban development will continue to grow, especially in the developing countries which are undergoing rapid urbanization. A useful way to clarify its ambiguity is to set up some working definitions. Some specific and narrow definitions do exist for special circumstances but there are no commonly accepted definitions. The working definitions can help to eliminate ambiguities and find out solutions and better alternatives to existing development patterns.

The conversion of agricultural land into urban land uses in the urbanization processes has become a serious issue for sustainable urban development in the developing countries. Take China as an example, it cannot afford to lose a significant amount of its valuable agricultural land because it has a huge growing population to feed. Unfortunately, in recent years, a large amount of such land have been unnecessarily lost and the forms of existing urban development cannot help to sustain its further development (Yeh and Li 1997, Yeh and Li 1998). The complete depletion of agricultural land resources would not be far away in some fast growing areas if such development trends continued. The main issue of sustainable urban development is to search for better urban forms that can help to sustain development, especially the minimization of unnecessary agricultural land loss. Four operational criteria for sustainable urban forms can be used: (1) not to convert too much agricultural land at the early stages of development; (2) to decide the amount of land consumption based on available land resources and population growth; (3) to guide urban development to sites which are less important for food production; and (4) to maintain compact development patterns.

The objective of this research is to develop an operational CA model for sustainable urban development. A number of advantages have been identified in the application of CA in urban simulation (Wolfram 1984, Itami 1988). Cellular automata are seen not only as a framework for dynamic spatial modelling but as a paradigm for thinking about complex spatial-temporal phenomena and an experimental laboratory for testing ideas (Itami 1994).

Formally, standard cellular automata may be generalised as follows:

$$S^{t+1} = f(S^t, N) \tag{1}$$

where S is a set of all possible states of the cellular automata, N is a neighbourhood of all cells providing input values for the function f, and f is a transition function that defines the change of the state from t to $t+1$.

Standard cellular automata apply a 'bottom-up' approach. The approach argues that local rules can create complex patterns by running the models in iterations. It is central to the idea that cities should work from particular to general, and that they should seek to understand the small scale in order to understand the large (Batty and Xie 1994a). It is amazing to see that real urban systems can be modelled based on microscopic behaviour that may be the CA model's most useful advantage. However, the 'top-down' critique nevertheless needs to be taken seriously. An example is that central governments have the power to control overall land development patterns and the amount of land consumption.

With the implementations of sustainable elements into cellular automata, a new paradigm for thinking about urban planning emerges. It is possible to embed some constraints in the transition rules of cellular automata so that urban growth can be rationalised according to a set of pre-defined sustainable criteria. However, such experiments are very limited since many researchers just focus on the simulation of possible urban evolution and the understanding of growth mechanisms using CA techniques.

The constrained cellular automata should be able to provide much better alternatives to actual development patterns. A good example is to produce a 'compact' urban form using CA models. The need for sustainable cities is readily apparent in recent years. A particular issue is to seek the most suitable form for sustainable urban development. The growing spread of urban areas accelerating at an alarming rate in the last few decades reflects the dramatic pressure of human development on nature. The steady rise in urban areas and decline in agricultural land have led to the worsening of food production and other environmental problems. Urban development towards a compact form has been proposed as a means to alleviate the increasingly intensified land use conflicts. The morphology of a city is an important feature in the 'compact city theory' (Jenks *et al.* 1996). Evidence indicates a strong link between urban form and sustainable development, although it is not simple and straightforward. Compact urban form can be a major means in guiding urban development to sustainability, especially in reducing the negative effects of the present dispersed development in Western cities. However, one of the frequent problems in the compact city debate is the lack of proper tools to ensure successful implementation of the compact city because of its complexity (Burton *et al.* 1996). This study demonstrates that the constrained CA can be used to model compact cities and sustainable urban forms based on local, regional and global constraints.

3. Suitability and constraints for sustainable urban forms using CA

In this constrained CA model, there are three important aspects of sustainable urban forms that need to be considered—compact patterns, land quality and the amount of land consumption. Compact patterns can be formed using some neighbourhood functions in computer simulation. It is possible to create compact patterns since cellular automata are fundamentally neighbourhood-based. The concern over land quality is also an important issue in sustainable urban development since land quality is a critical factor for agricultural production. The restriction of development in fertile land or sensitive areas needs to be implemented in the sustainable development model. There is also a need to properly arrange the amounts of land consumption in different periods to avoid the early depletion of land resources. This research will demonstrate that these three aspects can be well incorporated into the constrained CA through the use of local, regional and global constraints.

3.1. *State-based cellular automata*

In a standard CA model, the state is usually used as the main attribute to describe the development of a cell. Any cell cannot take on more than one state simultaneously, although the state can change from one to another in different periods. In urban simulation, the most general state for a cell is developed or not developed (alive and dead). The essence of cellular automata is that the states of the neighbouring cells influence the state of the central cell. Iterative looping rules are used, but defining the rules is not unique. A simple model is to project the state of a central cell using a 3×3 window to count the distribution of states in its neighbouring cells.

A simplified rule-based structure of this type of cellular automata may be defined as (Batty 1997):

IF any cell $\{x \pm 1, y \pm 1\}$ is already developed
THEN $P_d\{x, y\} = \sum_{\{i,j\} \in \Omega} P_d\{i, j\}/8$
&
IF $P_d\{x, y\} >$ some threshold value
THEN cell $\{x, y\}$ is developed with some other probability $\rho\{x, y\}$

where $P_d\{x, y\}$ is the probability of urban development for cell $\{x, y\}$, cell $\{i, j\}$ are all the cells which from the Moore neighbourhood Ω, including the cell $\{x, y\}$ itself.

The model indicates that cells developed in the neighbourhood cells can add some probability for development in the central cell. This sets off a 'relax' growth process in which cells can successively develop as soon as they come into contact with developed cells.

3.2. *Suitability-based cellular automata*

More sophisticated CA systems have been further developed to simulate urban growth through the concepts of 'development probability' and 'development suitability' (White *et al.* 1997, Wu and Webster 1998). This kind of simulation assumes a relation between the states (developed or not), development probability and development suitability:

$$S^{t+1}\{x, y\} = f(P_s^t\{x, y\}) \tag{2}$$

$$P_s^t\{x, y\} = f(DS_s^t\{x, y\}) \tag{3}$$

where $S\{x, y\}$ is the state at location $\{x, y\}$; $P_s\{x, y\}$ is the probability of transition to the state S at the location; and $DS_s\{x, y\}$ is the suitability of conversion to the state S. f is a transition function.

The conversion criterion is that cells with high scores of development suitability will first be selected for development. It is obvious that the CA simulation heavily depends on the calculation of development suitability based on neighbourhood configuration. The suitability of a cell for development is usually evaluated according to location factors and site properties. Much work has been done on the evaluation of land suitability, which usually involves multicritera evaluation (MCE) techniques (Yeh and Li 1998, Wu and Webster 1998).

Land suitability which describes the potential of a cell for a specific type of land use can act as an important constraint in the CA model. There are reasons to put suitability into the model for sustainable land use. Suitability is crucial to determine the use of land in urban planning to achieve efficiency, especially for sustainable land use. For example, we may allow faster urban development in less fertile land and more restricted or slower urban development in good agricultural land. Therefore, suitability also plays an important role in affecting the state or the transfer of the state of a cell in an idealised development pattern. One cell can take on more than one suitability score for different proposed types of land use. Land suitability is also subject to the land use change in a neighbourhood function (Yeh and Li 1998). Suitability scores should be re-computed in each iteration to achieve compatible land use. The model may be expressed as a two-dimension model, including states $S(t)$ and suitability $SS(t)$:

$$(S^{t+1}, SS^{t+1}) = f(S^t, SS^t, N) \tag{4}$$

where N is the neighbourhood providing input values for the transition function f.

3.3. *Constrained cellular automata*

Although constraints have been examined in some cellular automata models, they are used to make more reliable and reproducible predictions of actual urban land-use patterns (White *et al.* 1997). The constraints used are mainly related to land suitability according to accessibility that affects land development probability, such as cost distance to city centres, roads and railways. There is a general lack of consideration of other constraints of development, especially those related to sustainable development, such as environmental conservation. More constraints can be incorporated in cellular automata to ensure that urban growth will satisfy sustainable urban forms or at least find better urban forms.

Constraints for sustainable urban development can be generally classified into three types—local, regional and global constraints. It is possible to simulate idealised development or sustainable urban forms if these types of constraints are built within a CA model. Local constraints contain detailed spatial information for each cell, but regional constraints have only aggregated or partial-spatial information. Global constraints, however, are characterised by temporal or non-spatial information.

Local constraints can be represented by cell-based values or scores that influence the CA modelling process cell by cell. Regional constraints may only emphasize the differences of a geographical phenomenon among larger areas, such as towns. The effects of administrative boundaries could be crucial in influencing development patterns. For example, the estimation of population growth is important in deciding per-capita land consumption in a town. Local governments often report much higher growth rates to higher level governments for obtaining larger quota of land for development. This can significantly exaggerate the consumption of agricultural land in the towns that have low levels of 'sustainable' consciousness. However, regional constraints can be applied to reduce the possibility of irrational development patterns according to the detailed situations of each town. Global factors could temporally change in correspondence with the dynamics of land resources and the decisions from national and provincial governments. This type of constraint can be used to control the amount of land consumption in the CA modelling. The combination of local, regional and global constraints is expected to produce effects in eliminating unsustainable development patterns as far as possible.

The proposed constrained CA model that stresses the importance of constraints as well as states is as follows:

$$\begin{aligned} P_d'^t\{x,y\} &= f(S^t\{x,y\}, \mathrm{cons}_{ld}^t\{x,y\}, \mathrm{cons}_{rd}^t\{x,y\}, \mathrm{cons}_{gd}^t\{x,y\}, N) \\ &= f(S^t\{x,y\}, CONS_d^t\{x,y\}, N) \end{aligned} \tag{5}$$

where $P_d'^t\{x,y\}$ is the development probability of cell $\{x,y\}$ at time t; $S^t\{x,y\}$ is the state of cell $\{x,y\}$ at time t; $cons_{ld}^t$, $cons_{rd}^t$ and $cons_{gd}^t$ are the evaluated scores of local, regional and global constraints respectively; $CONS_d^t$ is the total evaluated constraint scores by combining all the constraints; and N is the neighbourhood of cell $\{x,y\}$.

The model can be decomposed as a standard CA model, $f(S^t\{x,y\}, N)$, plus the constraint coefficient $CONS_d^t\{x,y\}$. It becomes:

$$P_d'^t\{x,y\} = f(S^t\{x,y\}, N) \times CONS_d^t\{x,y\} \tag{6}$$

Constraint scores for development can be regarded as a scalar or a birth rate to readjust the development probability that is calculated from a standard CA model. The scores continuously range from 0 to 1. The maximum value of the scores is 1, indicating 100% support for development. The minimum value is 0, denying any possibility of development.

MCE techniques can be applied to estimate development suitability which is usually dependent on more than one factor (Wu and Webster 1998). The techniques can also be applied to obtain the final score of constraints. This is:

$$CONS_d^t\{x,y\} = \left(\sum_{i=1}^{k} W_i cons_{id}^t\{x,y\}\right) \prod_{i=k+1}^{n} cons_{id}^t\{x,y\} \tag{7}$$

where w_i is the vector of weights for constraints. $1 \leqslant i \leqslant k$ are non-restrictive constraints whereas $k+1 \leqslant i \leqslant n$ are the restrictive constraints.

Non-restrictive constraints are the constraints that have some influences but do not have critical impacts on the modelling process. Restrictive constraints are those that have important effects on the modelling process. For example, the barriers of small water areas or hills can pose some difficulties for urban development and they can be regarded as non-restrictive constraints. Barriers such as steep mountains or major agricultural areas can be used as restrictive constraints in restricting urban development from taking place there. In our modelling process, local, regional and global constraints are restrictive factors since they are considered as equally important in creating sustainable urban forms. The formula can be simplified as:

$$CONS_d^t\{x,y\} = \prod_{i=1}^{n} cons_{id}^t\{x,y\} \tag{8}$$

The combination of local, regional and global constraints can be processed cell by cell. Regional and global constraints which are aggregated need to be desegregated into each cell before the combination. Global constraints, which are functions of time, enable the system-wide growth rate to be changeable and controlled across time. An example is the optimal arrangement of a given amount of resource consumption for different periods. We have proposed an 'equity' model to allocate the amounts of land consumption for different planning periods based on some sustainable criteria (Yeh and Li 1998). The optimal allocation can be used as a global constraint so that too much land consumption at an early stage is avoided. It is easy to control the rate of urban growth using the global constraint. A value of 0 will be applied for the global constraint when the growth reaches the optimal consumption for a period. Then the product of all constraint scores becomes 0 and the system stops growing. The global constraint is important in keeping urban growth within a sustainable rate.

There is a unit problem in standard CA simulation which is operated on a cell by cell basis. A cell which is the basic unit of cellular automata has only a binary value—1 for successful development and 0 for non-change. There are no intermediate values for these 'black or white' cells. This raises a problem when there is a need to differentiate growth rates between cells or for a cell between different periods. The 'grey' state of a cell can be used to overcome this unit problem by assign a value that ranges from 0 to 1 for each cell in the CA model. It can serve two purposes. First, the 'grey' state can accurately represent the degree or percentage of development for a cell. 'Grey' cells are those of partial development. However, a 'grey' cell could be divided into many absolute 'black' sub-cells and 'white' sub-cells if the resolution were increased. Secondly, 'grey' state may also be regarded as a useful dummy variable in representing the accumulation of development or development probability during the iterations of the CA model.

In our CA model, 'grey' state $G_d\{x,y\}$ of a cell is defined to reflect the developed (urbanised) percentage of the cell $\{x,y\}$. First, the development probability of a cell at time t can be calculated based on its neighbouring states according to standard cellular automata:

$$P_d^t\{x,y\} = f(S\{x,y\}^t, N) \tag{9}$$

where N is the neighbourhood of the cell $\{x,y\}$.

The additional developed percentage or additional 'grey' state $\Delta G_d^t\{x,\mathrm{y}\}$ of a cell at the time t is proportional to the probability and also subject to the combined constraint score.

$$\Delta G_d^t\{x,y\} = P_d^t\{x,y\} \times CONS_d^t\{x,y\} \tag{10}$$

The final 'grey' state is the accumulation of the developed percentages for each step of the iteration.

$$G_d^{t+1}\{x,y\} = G_d^t\{x,y\} + \Delta G_d^t\{x,y\} \quad G_d\{x,y\} \in (0,1) \tag{11}$$

The 'grey' state should be kept within the range of (0,1). Therefore, $\Delta G_d^t\{x,y\}$ should be assigned to 0 when $G_d^t\{x,y\}$ reaches 1.

An iteration formula for the constrained CA model based on the 'grey' value of a cell is therefore as follows:

$$S^{t+1}\{x,y\} = \left[\begin{array}{ll} \text{developed} & (G_d^t\{x,y\} = 1) \\ \text{partial developed} & (0 < G_d^t\{x,y\} < 1) \\ S^t\{x,y\} & (G_d^t\{x,y\} = 0) \end{array}\right. \tag{12}$$

4. Implementation and discussion

The constrained CA model for sustainable land development was implemented in the ARC/INFO GRID environment using the Arc Macro Language (AML). The development of the CA model within a GIS can facilitate the convenient access to the land use information in the GIS database. The GIS database consists of land use maps, soil maps, economic data and the monitoring results of land use change detected from remote sensing for the Peal River Delta. The CA model was applied to a city, Dongguan, in the Pearl River Delta as a case study. The essence of the CA model is that constraint space plays an important role in regulating the growth of 'cellular cities'.

Before the application, the CA model was applied to simplified artificial cities for the easy identification of modelling effects. Figure 1 is the simulation result using artificial constraint space and cities. The result clearly demonstrates that the CA model is straightforward in allowing constraints to shape urban growth. Much better urban forms can be obtained by reducing urban encroachment on the 'restricted areas' according to the constraint scores. Urban growth will be frozen in the areas

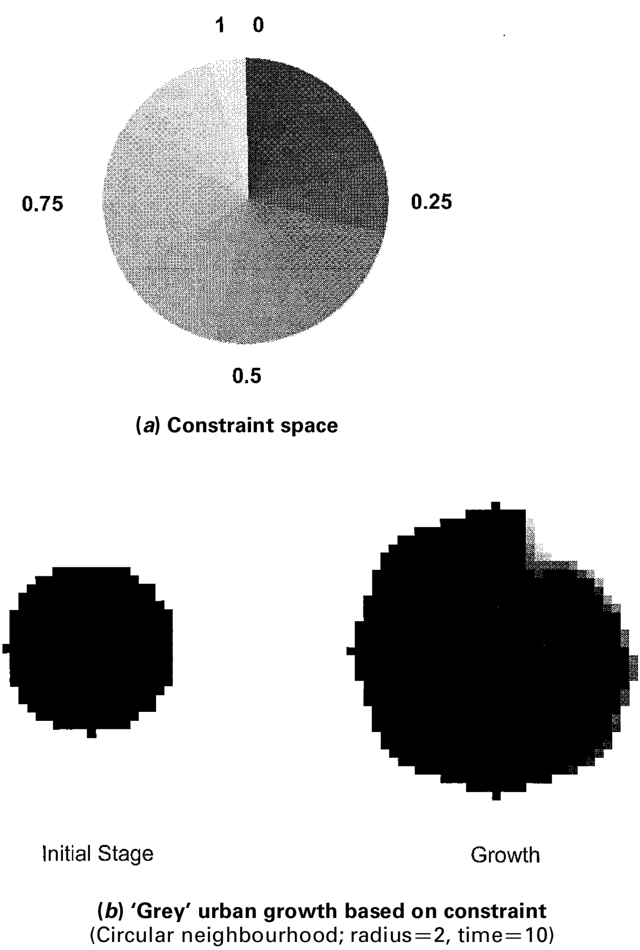


Figure 1. Constraint space and cellular automaton. (*a*) Constraint space (*b*) 'Grey' urban growth based on constraint (Circular neighbourhood; radius = 2, time = 10.

with constraint score equal to 0. It is obvious that the score of 0 or low values should be applied to those environmentally sensitive areas or important agricultural production areas to formulate better urban development scenarios. Figure 2 shows that the model can also be valid for regulating polycentric urban growth.

In this study, the circular neighbourhood is used to improve model accuracy. The circular neighbourhood is better than a rectangular neighbourhood (the Moore neighbourhood) because no bias exits in all directions (figure 3). In figure 3(*a*), the points of A, B, A′, and B′ should have the same neighbourhood for a circular object. However, the configuration of neighbourhood by rectangles produce a discrepancy of neighbourhood between A and B. Thus, the simulation from the rectangle neighbourhood can produce significant distortions, compared with that from the circular neighbourhood (figure 3(*b*)).

A simple way to define constraint space is to use agricultural suitability in this constrained CA model. Agricultural suitability can be assessed from a series of site information that indicates agricultural production potential. Development suitability scores that range from 0 to 1 can be defined as the inverses of agricultural suitability scores. Then good-quality agricultural land will correspond to areas of low development suitability scores. Restricting development in areas of high development suitability scores and relaxing development in other areas as the replacement can help to sustain future food supply.

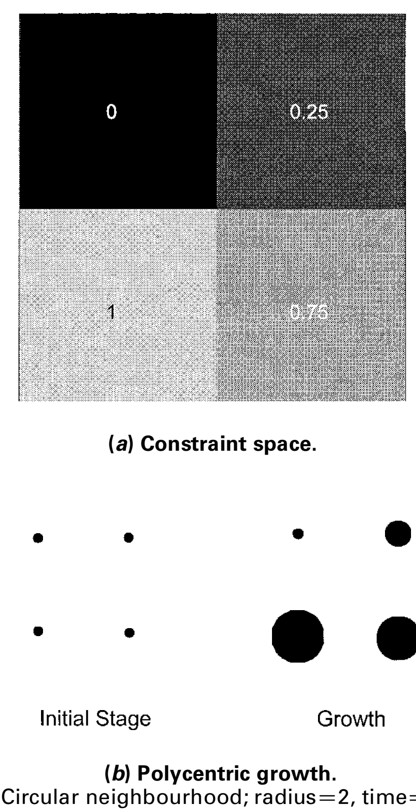


Figure 2. Constraint space and polycentric growth. (*a*) Constraint space. (*b*) Polycentric growth. (Circular Neighbourhood; radius = 2, time = 5).

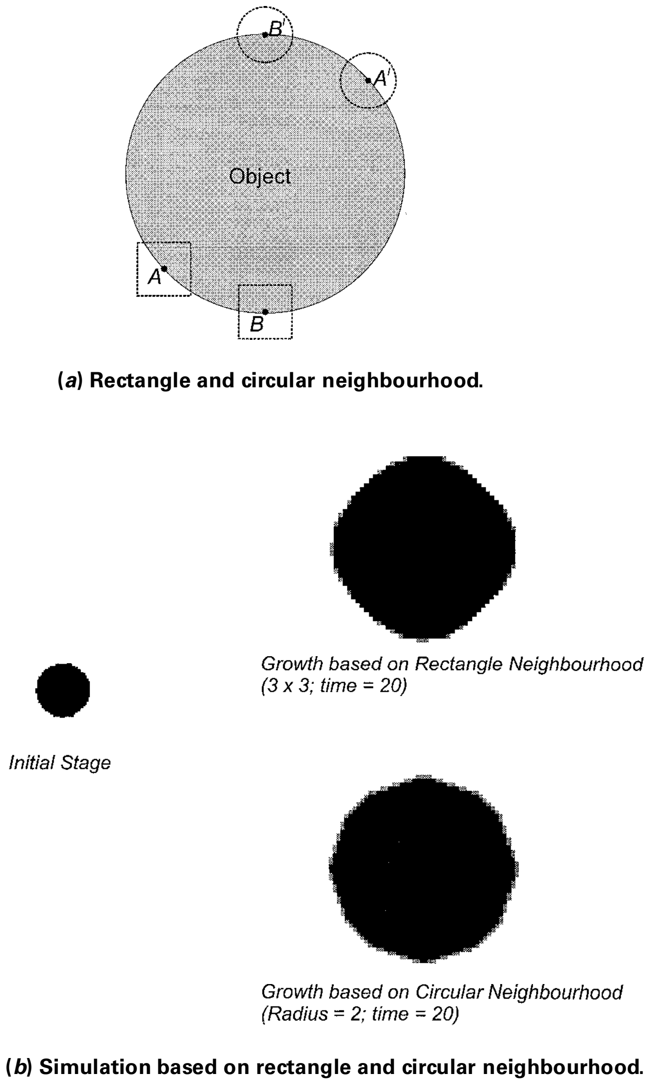


Figure 3. Rectangle and circular neighbourhood for the CA model. (*a*) Rectangle and circular neighbourhood. (*b*) Simulation based on rectangle and circular neighbourhood.

In this CA model, development control is enhanced by the transformation of development suitability scores into constraint scores using a power function. A non-linear transformation of development suitability scores into constraint scores can allow a control parameter k to be added into the modelling process. The advantage of using the power function is its simplicity and effectiveness in controlling development patterns through the parameter k. A set of transformation curves can be produced from different values of parameter k. This is especially useful when there is a need to put more weight on protecting the best quality agricultural land by choosing proper k values. The power transformation is defined as:

$$CONS = DS^k \tag{13}$$

where $CONS$ is the constraint score and DS is the development suitability score.

Figure 4 is the result of the power transformation with different values of k. A normal linear transformation can be obtained when $k=1$. It is apparent that no constraints will be applied to the model when k is chosen as 0. It can be easily seen that constraint scores will be closer to 0 for good-quality agricultural land when the values of k are higher than 1.

The constrained CA model is applied to an actual city, Dongguan in the Pearl River Delta, the fastest growing region in China. A great amount of agricultural land has been lost in this region because of rapid land development and poor land management (Yeh and Li 1997). The constrained CA model is useful to generate some much better urban forms so that sustainable land development can be achieved in the region. The city covers an area of 2465 km^2 with 29 towns and a city proper. Most of the best agricultural land is concentrated at the north-west corner of the city. There is a strong challenge in protecting agricultural land during the rapid urbanisation process. One may argue that strict prohibition of land conversion is unrealistic. However, the constrained CA model can be used to find out suitable places for urban development and to regulate existing urban forms toward much better ones.

The basic data were mainly from TM satellite data with 30-m resolution on the ground. Agricultural suitability maps were produced mainly based on information from soil and slope maps. The data set was converted into a resolution of 50 m on the ground with 619 pixels $\times$ 889 pixels. The CA model used a circular neighbourhood with a radius of 2 pixels which included an area of about 3×10^4 m^2 on the ground. The transition rules of this CA model were mainly based on the calculation of the 'grey' state of each cell which was subject to development probability and a series of constraints. The circular neighbourhood was used to count development probability for a cell. The 'grey' state of a cell was calculated according to equations (6–13). The time steps of simulation (t) for each scenario were decided to ensure that the amount of final land consumption would be equal to the actual or optimal.

Figure 5 shows the transformation of agricultural suitability into local constraint scores using a power function. In the transformation function, different values of k were used to compare the effects on the protection of the best agricultural land.

Figure 6 is the simulation results when these constraint scores are applied in

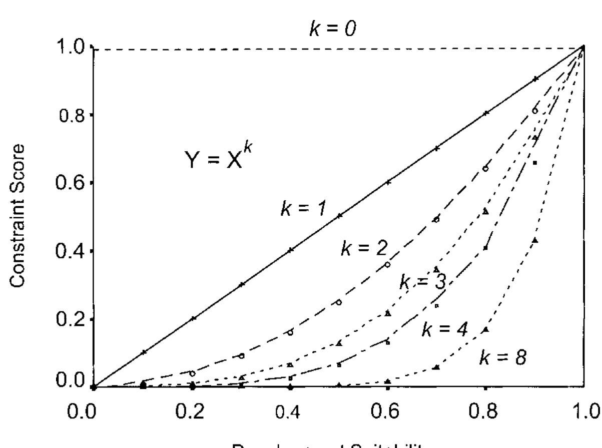


Figure 4. Power transformation of development suitability into constraint score.

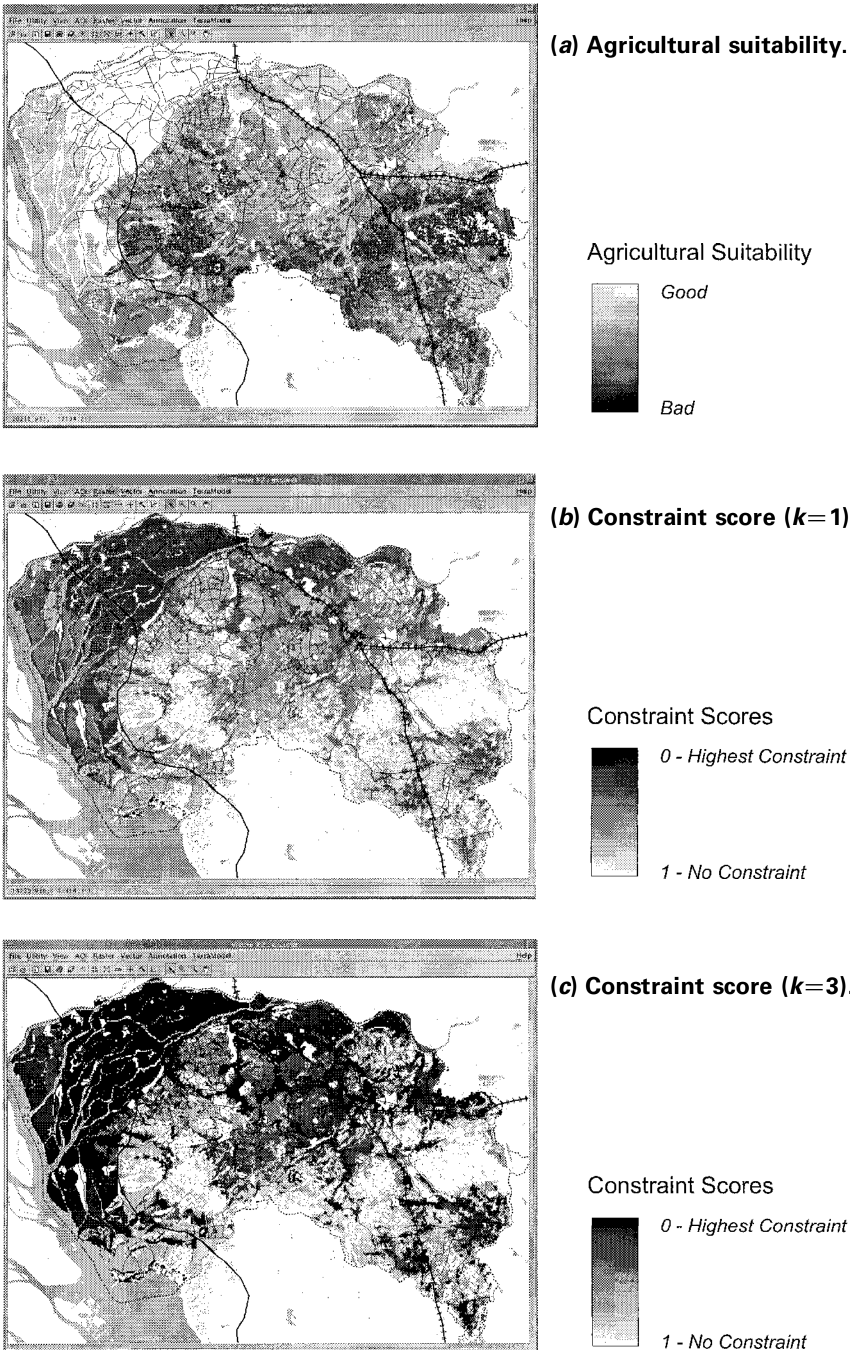
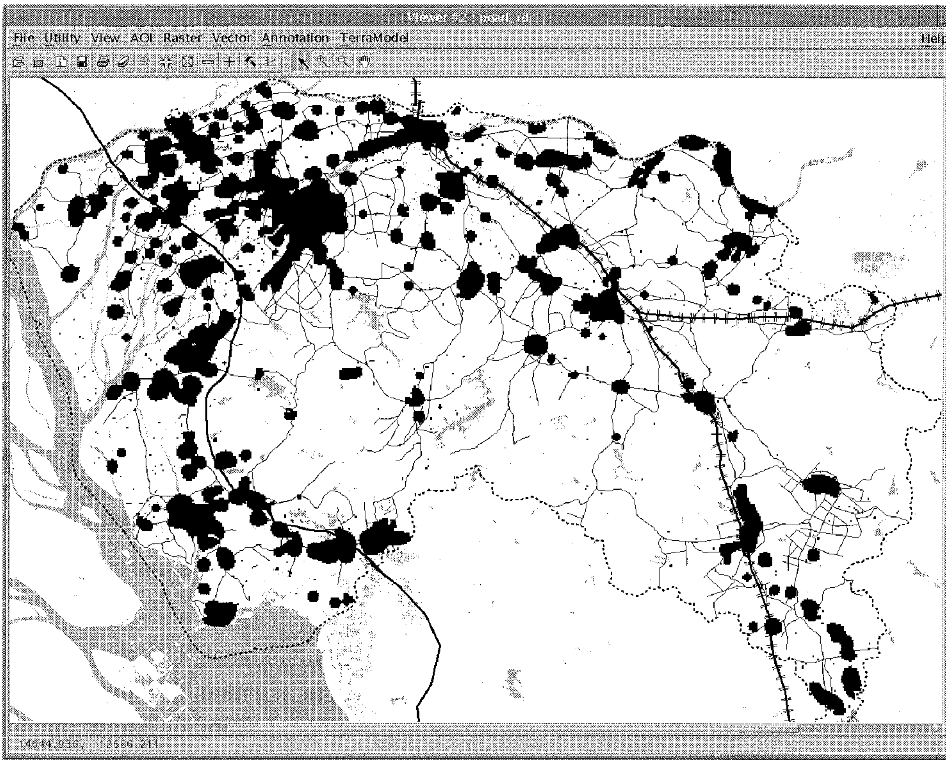


Figure 5. Agricultural suitability and constraint scores. (*a*) Agricultural suitability. (*b*) Constraint score ($k=1$) (*c*) Constraint score ($k=3$).

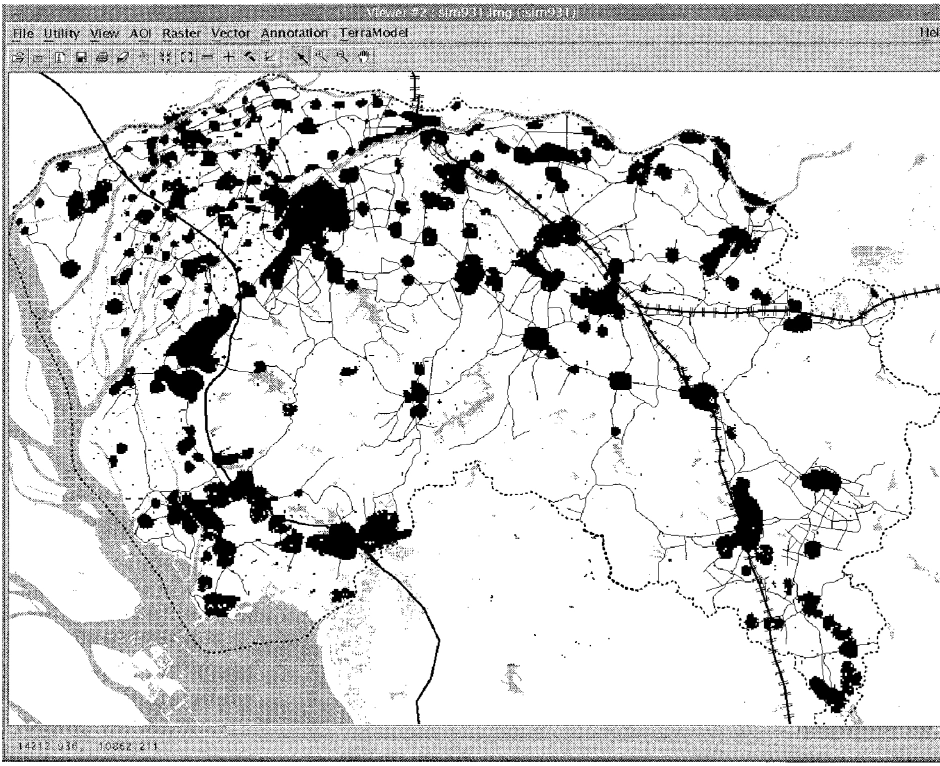


(*a*) Loss of the best agricultural land
(k=0, without constraints; t=5)

Figure 6(a). Controlling the loss of the best agricultural land using suitability constraints.

searching for much better urban forms for the city. The 1988 and 1993 TM images were used to derive the urban areas in 1988 and 1993. The simulation started based on the urban areas of 1988 and tried to search for better alternatives for 1993 using the same amount of land consumption. Figure 6(a) is the simulation result without suitability constraints ($k=0$). Its initial stage is based on the urban areas from the classification of the 1988 satellite image. If land development proceeded according to this scenario, a lot of land loss might take place in the north-west part of the city where the best of agricultural land is concentrated. With the use of constraint factors in the constrained CA model, urban encroachment on the best land can be reduced by using less fertile land as a replacement of the more fertile land for development. The use of linear transformation of development suitability into constraint score ($k=1$) produces less loss of fertile land although the land consumption is the same (figure 6(b)). There would be much less of fertile land lost when the non-linear transformation ($k=3$) is used (figure 6(c)).

An indicator related to suitability loss is used to assess the above different scenarios. Urban land development will encroach on agricultural land which has an attribute of agricultural suitability. The conversion of agricultural land will accompany suitability loss because of the removal of agricultural production potential. The



(*b*) Controlling urban encroachment on the best agricultural land
(k=1, with normal constraints; t=10)

Figure 6(*b*). Controlling the loss of the best agricultural land using suitability constraints.

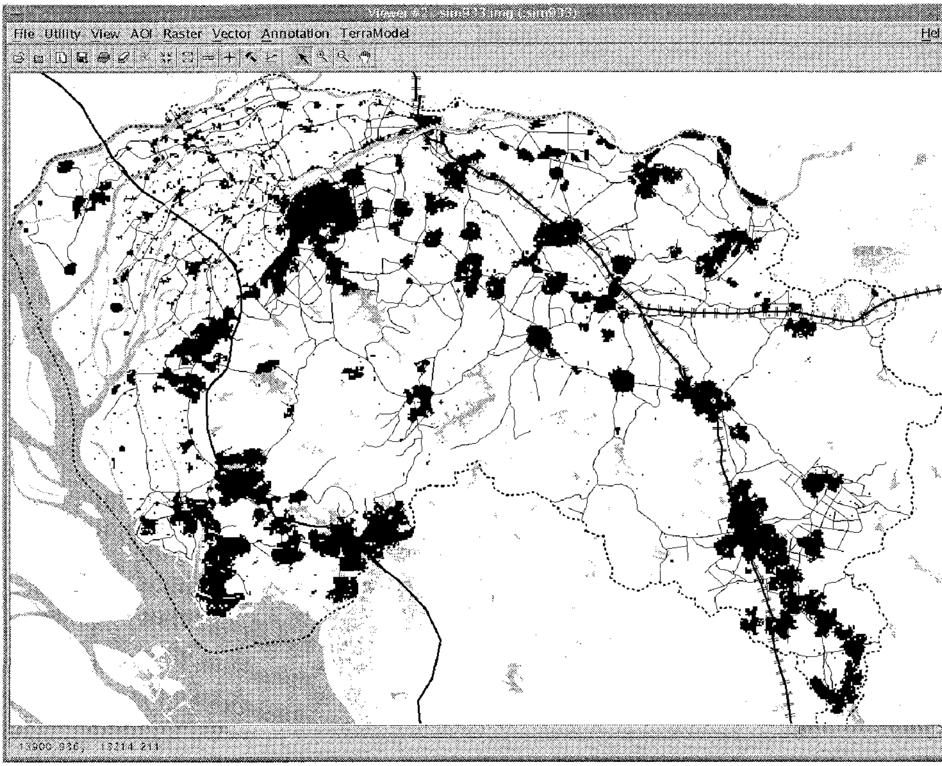
measurement of suitability loss can provide an indicator for the assessment of development impacts. The indicator of measuring suitability loss is as follows:

$$S_{loss} = \sum_{\{x,\,y\}\,\in\,\Omega} \sum_{i} S(i, \{x,y\}) \tag{14}$$

where S_{loss} is the total suitability loss and $S(i, (\{x,y\})$ is the suitability for agricultural type i at cell $\{x,y\}$; and Ω is the set of all cells of land loss.

The effects of CA modelling for protecting good agricultural land can be demonstrated by the plot of suitability loss and land consumption. Figure 7 is the scatter plot of suitability loss and land consumption for different values of k. There is a linear relationship between suitability loss and land consumption. The slope is reduced if higher values of k are applied. This indicates that higher values of k can lead to a lesser amount of suitability loss for the same amount of land consumption.

More complicated factors besides agricultural suitability can be embedded into the constrained CA model to reflect other environmental settings for sustainable urban forms. Land resources and economic factors vary regionally and globally. For example, per-capita agricultural land resources may not be the same among towns and this should affect land supply regionally. Land supply may also change globally



(c) Stricter control of urban encroachment on the best agricultural land
(k=3, with stricter constraints; t=24)

Figure 6(c). Controlling the loss of the best agricultural land using suitability constraints.

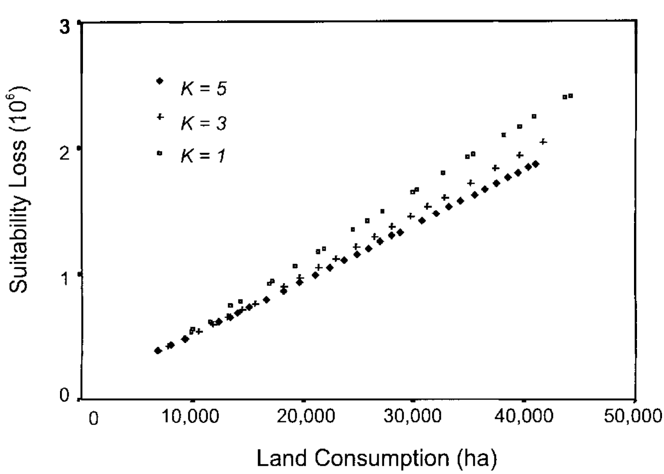


Figure 7. Linear relationships between land consumption and suitability loss for various k values.

because of government policies and intervention. Development suitability and constraints can be defined with reference to these changeable regional and global factors. The integration of CA and GIS provides a useful tool to explore sustainable urban forms under different development scenarios.

An example of using regional constraints is to plan urban growth rate based on the percentage of available land resources by towns. It seems reasonable that the rates of urban growth should be based on available land areas (land supply). There is evidence that land resources vary differently among towns (Li 1998) and different growth rates can be applied to differentiate them. One may argue that local (neighbourhood) constraints could be built to deal with the differences. However, actual land use planning is usually made on an aggregated basis for an administration unit (town). The aggregated data of population, land resources and economy within the administration boundary will usually decide the scale and types of land use patterns.

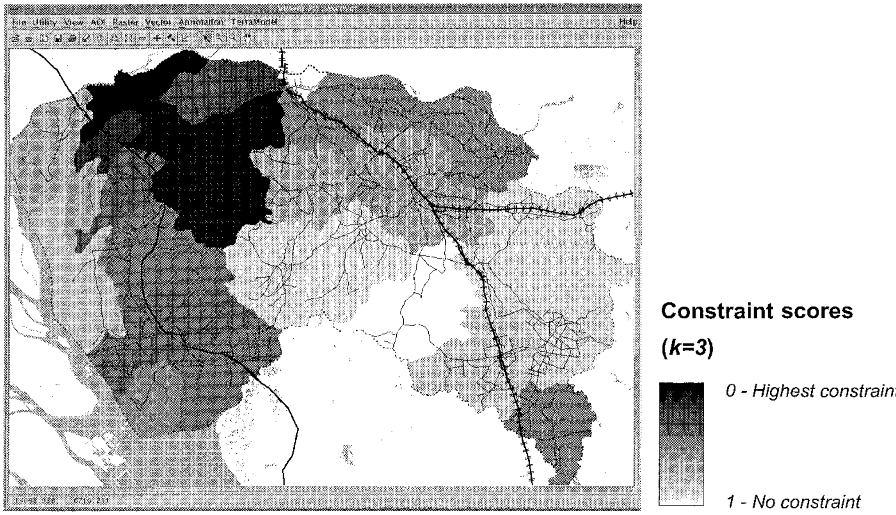
The percentage of available land for conversion by towns was calculated using satellite data. Figure 8(*a*) shows the constraint scores that are transformed from the percentage of available land in each town. As the result of the constraint, towns with higher percentage of available land will be allowed to grow faster in the CA model. In contrast, the growth in the towns with lesser percentage of available land will be restricted by applying lower growth rates. The modelling results are shown in figure 8(*b*) in which the non-linear transformation ($k=3$) was used to convert the percentages into constraint scores.

The combination of local constraints and regional constraints was carried out by the product of these factors. Figure 9(*a*) is the product of agricultural suitability constraint and available land constraint. The objective is that urban growth should be restricted in the areas of fertile agricultural land (cell-based) and less available land resources (town-based). Global constraints were also embedded in the constrained cellular automata. The essence of the constraints is to control land consumption across time. We obtained the amounts of optimal land consumption for different planning periods using an 'equity' model according to the criteria of sustainable development (Yeh and Li 1998). In the CA modelling, a global constraint score of 0 is applied when urban growth has reached its optimal land consumption. According to the model, we find that the actual land consumption in 1988–93 is too much due to wasteful use of land resources.

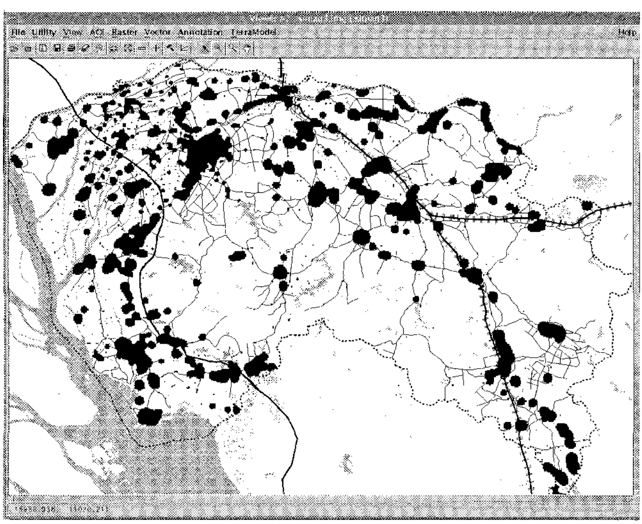
Figure 9(*b*) is the modelling results when the product of local constraint score, regional constraint score and global constraint score is applied to derive optimal development patterns for the city. The optimal land consumption was decided according to the 'equity' model. The simulation stopped when it reached the optimal land consumption. The initial stage was based on the urban areas of 1988. The simulation attempted to find the reasonable land consumption and locations of urban development for 1988–93. Based on the model, a lesser amount of agricultural land loss would be obtained and more efficiency could be achieved by controlling land consumption and selecting much better development sites.

In this study, the 'grey' state of a cell can range from 0 to 1. There are other cells with intermediate values which represent partial development. However, the number of these cells is small since they will soon become fully developed after a few iterations.

The model developed here is related to the previous model that used the same data set for simulating sustainable land development (Yeh and Li 1998). They are two different models with respect to their framework and performances. The novelty of the previous model is to provide an 'equity' allocation method within GIS, but



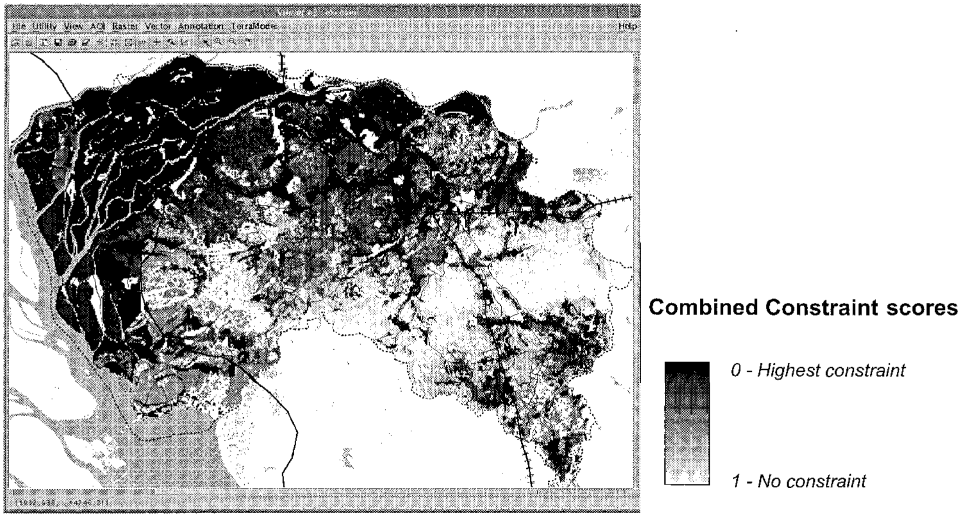
(*a*) Regional constraints — available land resources by towns.



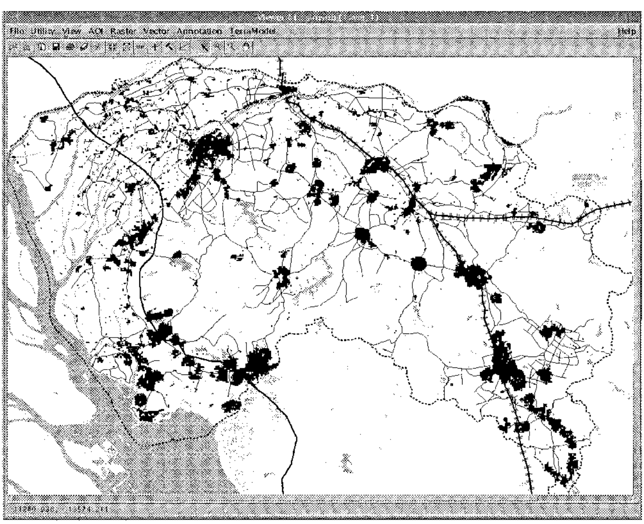
(*b*) Urban growth based on land resources by town (*k*=3; *t*=37).

Figure 8. Regional constraints and urban growth. (*a*) Regional constraints—available land resources by towns. (*b*) Urban growth based on land resources by town ($k=3$; $t=37$).

the model has some weaknesses in site selection. The procedures of site selection in *model 1* are not based on CA techniques and are time-consuming. The second model can easily incorporate various types of complicated constraints using state of the art CA techniques. This can allow the development patterns to be easily controlled by constraints and parameters. The results from model 2 are more encouraging in terms



(*a*) Product of local constraints and regional constraints.



(*b*) Urban growth based on local, regional and global constraints (*k*=3; *t*=22).

Figure 9. Local, Regional and Global Constraints for Sustainable Urban Forms. (*a*) Product of Local Constraints and Regional Constraints (*b*) Urban Growth Based on Local, Regional and Global Constraints (k = 3; t = 22).

of the compactness and suitability loss generated. The compactness index *CI* can be calculated by:

$$CI = \sqrt{S}/P \tag{15}$$

where S is the total area and P is the perimeter of land development or land loss.

It is obvious that a larger value of CI is preferable for compact development patterns. Table 1 is the comparison of compactness and suitability loss for actual land development and the results from *model 1* and *model 2*, using equations (14) and (15). It can be found that much better results are produced in *model 2*. Furthermore, the run time for *model 2* is about a few minutes whereas the run time for *model 1* is about an hour (using the same Sun Ultra workstation and ARC/INFO GRID). Apparently, *model 2* has much better performance with regards to the output and run time.

Table 1. Comparison of the efficiency between actual development, *Model 1* and *Model 2* with the same amount of land consumption in 1988–1993.

	Compactness index (CI)	Suitability loss (S_{loss})
Actual development	1.78	9.26E+06
Model 1	4.20	8.90E+06
Model 2	9.79	1.31E+06

It seems that this proposed CA model is not related to urban suitability but more to agricultural suitability. This raises the questions on how to take urban suitability into account and keep the urban system sustainable in this model. We consider that the local, regional and global constraints embedded in this model are most important in generating sustainable urban growth in many developing countries where the loss of agricultural land to urban development is serious. This model uses agricultural suitability as an important local constraint and also uses other factors, such as available land areas and population growth as regional and global constraints. Without using these constraints, the model is no different from standard CA models which simulate urban growth that is mainly based on urban suitability using the neighbourhood functions. There are conflicts of land allocation based on agricultural suitability and urban suitability (Yeh and Li 1998). In this constrained CA model, the k parameter of the model is used to balance between the constraints and neighbourhood functions. All the influences of agricultural suitability and other constraints will be eliminated when the value of k is assigned to 0. Higher values of k will produce development scenarios that give more weights to agricultural suitability. The choice of the appropriate k value is dependent on the decision-makers who may consider political issues as well as resource factors, rather than simply the model, in their decision making. This model provides an opportunity for the decision-makers to see the results of different land development controls by using different k values. This study has demonstrated that the model is capable of producing compact development patterns and conserving fertile agricultural land, both are important issues in the planning of sustainable urban development in many developing countries.

5. Conclusion

The protection of valuable agricultural land is important in many developing countries where cities are growing rapidly. In China, cities are usually expanding without properly considering land suitability and environmental impacts. Recent rapid land development has been accompanied by the loss of large amounts of fertile agricultural land. This study demonstrates that CA can be used to simulate urban development based on constraints that can reflect our environmental concerns. The objective is to produce sustainable urban forms as alternatives to the existing development patterns. The study has suggested that programming the CA inside a GIS can be as a useful planning tool to model urban development under complicated and changeable environmental factors. The results of modelling can provide useful guidelines for policy making and urban management in developing countries, especially in China where urban areas are rapidly expanding in a highly dispersed pattern.

Cellular automata have been widely applied to the simulation and prediction of possible urban development according to empirical data and rules. However, this paper provides a prototype implementation of CA that can be used in urban planning by using various kinds of constraints which are associated with sustainable development criteria. There is a need to broaden standard CA models in solving growing environmental problems based on the principles of sustainable development. Local, regional and global constraints can be embedded in CA models and thus regulate urban development toward better urban forms. These types of constraints are equally important in affecting modelling results. This is quite different from the standard cellular automata in which only the property of locality has a unique role.

The concept of the 'grey' state of a cell is proposed to represent the level of development of a cell. It can overcome the limitations of absolute 'black' and 'white' cells that are used in standard cellular automata. The 'grey' state is the basis of the constrained CA model. The advantages are that constraint scores can be conveniently included in the model and the iteration equations of the model can be executed exactly using intermediate values of the 'grey' state.

There are significant conflicts between protection of good-quality agricultural land and urban development because good-quality agricultural land is often suitable for urban development. This model provides an operational framework for balancing the two different options based on CA techniques. Particularly, a power function and k parameter are used in the transformation of constraints for regulating urban development. This can allow the users to interactively choose different k values and find better urban forms based on the background of available land resources and other political situations. More emphasis will be put on the strict protection of good-quality agricultural land by increasing the value of k.

The comparison of actual land development and modelling results reveals that this model can produce much better urban forms in terms of compactness and suitability loss. This is very important for sustainable urban development because agricultural land loss is very severe in many developing countries. The comparison also indicates that this model has also produced more plausible results than a previous model that we have developed using the same data set (Yeh and Li 1998).

The integration of cellular automata with GIS could be of mutual benefit. Cellular automata can provide the much lacking simulation models in GIS. The use of GIS could enable cellular automata to go beyond theoretic constructs and become more realistic by taking into account real world data, factors and constraints in their modelling. The incorporation of various kinds of constraints in cellular automata can enable planners to compare the costs and benefits of different development scenarios that are necessary for the formulation of plans for sustainable cities.

CA models can be completely developed within GIS for easily accessing the information stored in the GIS database during the modelling processes. Constraints for modelling sustainable urban growth can be defined using GIS and remote sensing data. Neighbourhood functions can be calibrated using multi-temporal remote sensing data. The inventory of land use and evaluation of land resources are prerequisites for the modelling of land development. Remote sensing can be used to obtain land use information which is then transformed into GIS for analysis and modelling. The development of CA within GIS greatly enhances the ability of dynamic spatial modelling within GIS. Other researches also support that integrated CA-GIS approaches can enhance the current poor modelling capability of GIS (Park and Wagner 1997).

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