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USING A GIS-BASED CELLULAR AUTOMATA SPATIAL MODEL FOR PLANNING AND POLICY EVALUATION: A CASE OF SEBERANG PERAI, PENANG, MALAYSIA

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Kebanyakan negara sedang membangun mengalami pembandaran yang pesat kesan langsung daripada perkembangan dalam sektor perindustrian dan perumahan. Ini telah membentuk satu cabaran baru kepada jururancang dan pembuat dasar di negara tersebut. Namun pada masa kini, tidak banyak kajian tentang pengurusan dan perancangan bandar dijalankan di negara-negara ini. Artikel ini memapar potensi aplikasi model GIS-berasaskan Cellular Automata dalam perancangan dan penilaian strategi perancangan di Seberang Perai, Pulau Pinang, Malaysia. Model ini dibentuk dengan menggunakan kaedah penilaian pelbagai kriteria dan cellular automata dalam persekitaran Sistem Maklumat Geografi. Ia dibentuk dengan menggunakan data guna tanah 1990 dan dinilai dengan menggunakan data guna tanah 1998. Model ini berpotensi untuk digunakan dalam meramal pembangunan dan perkembangan bandar di Seberang Perai berdasarkan strategi pembangunan yang dicadangkan di dalam Rancangan Struktur Seberang Perai sehingga tahun 2010.

INTRODUCTION

Rapid urbanization in many developing nations has created many challenges to planners and urban managers (Devas and Rakodi, 1993; Chougill, 1994). For example, urban population in developing nations has increased from less than 300 million in 1950 to 1.1 billion in 1985, and it was projected to reach 4 billion in 2025 (UNCHS, 1996).

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Malaysia, for example, has experienced rapid urbanisation due to industrialization and related residential growth. For example, between 1970 and 1991 its urban population increased from 2.5 million to 8.9 million. Current planning policy and its related projection suggest that this trend is expected to continue at least until 2020 where total population is forecasted to increase from 17.6 million in 1991 to 40.6 million by 2020 (Department of Statistics, 1996; 2000). Such an increase in urban population will result in a transformation of the physical appearance of many cities in Malaysia (Morshidi *et al.*, 1999; Suriati, 1999).

Urban population growth has resulted in an increased pressure on land for residential and related services (Devas and Rakodi, 1993). At present, however, Malaysia lacks a cohesive planning policy to guide urban development (Goh, 1991). Current planning policy, the Town and Country Planning Act of 1976 requires local authorities to have Structural Plan and Local Plan to control and guide urban growth and development. However, the preparation of these plans in many cases takes a long time to be completed. Thus, by the time it is completed, it will become obsolete since socio-economic conditions change rapidly (Ibrahim and Abdul Hadi, 1992). Furthermore, the documents and maps are prepared in manual forms, which are difficult to be used for further analysis (Lee and Tan, 2001). In relation to the problem of the Structural Plan, many local authorities do not have an established planning information system (Goh, 1991). Thus, in order to undertake urban planning programs, it has to start with data collection and database management, which in many cases costly and time consuming to be conducted (Narimah, 2002). Furthermore, land use allocation is conducted in *ad-hoc* subjective fashion on the basis of the knowledge and experience of a small number of local planners and suggestions made by private consultants in the form of structural plan. As a result of such approach, there is no clear cohesive policy on land allocation (Goh, 1991). Therefore, there is no clear knowledge of the expected urban spatial pattern that may result from such land use allocation.

In order to manage urban growth effectively, there is a need to develop a planning tool that can be used to identify, map, locate and predict areas undergoing development pressure and evaluate different planning strategies.

Geographic Information Systems (GIS) have been used to evaluate the distribution of land use activities, to monitor land use changes, and to model urban spatial growth. It is an appropriate technology to manage large amounts of information on urban areas (Scholten and Stillwell, 1990; Yeh, 1999). This technology can be coupled with spatial models in order to understand the dynamics of urban development and to evaluate the relationship between different factors influencing urban growth and development (Batty and Xie, 1994).

The aim of this paper is to describe an initial attempt to develop a spatial temporal dynamic model using GIS and Cellular Automata (CA) approaches. From the knowledge and experience of the author, there has been no attempt to develop such model that focuses to Malaysian context (Narimah and Ruslan, 2001). Thus, this paper attempts to generate ideas, pave a way for subsequent studies and development and uses of urban spatial models in Malaysia.

CELLULAR AUTOMATA MODEL

Cellular Automata model has gained significant interest in the recent literature since it is a powerful modelling technique that can be applied to model complex dynamic systems. It has been use to simulate either synthetic or real cities (Batty and Xie, 1994; Clarke *et al.,* 1997; Engelen *et al.* 1999). Cities, like most geographical phenomena, are dynamic and complex nonlinear systems, which are difficult to model using current GIS functionalities. Thus, CA-spatial model can be use to imitate the behaviour of urban spatial growth on the basis of simple and realistic transition rules.

CA was first devised by John von Neumann and Stanislaw Ulam in the 1940s as a framework for investigating the logical underpinnings of life. They were trying to explore the possibility of using purely mathematical formulation to reproduce biological automata (Batty and Xie, 1994; Torrens, 2000). Tobler (1979), then, used a similar concept to describe a geographical modelling approach to model land use changes. CA has five basic elements: space, state, neighbourhood, transition rules and time steps (Couclelis, 1985). The cell space on which cellular automaton operates may be considered equivalent with an urban environment (Batty *et al.*, 1997; Torrens, 2000). Cells can be used to represent any zonal geography within a city: land parcel or administrative districts. The cell states represent any attribute of the urban environment such as land use (industrial or residential), density (high density or low density) or land cover (agriculture, built-up areas). Neighbourhoods in urban CA represent the spheres of influence or activity within the city such as the commuting distance (Torrens, 2000). The dynamics of change in the model is governed by a transition rule, which can be devised to emulate the real world through the algorithms within the simulation. The transition rule applied in the model is uniform, where at each iteration, cells change simultaneously.

GIS technology has been used to store and manage spatial information, to analyse, to manipulate and to display spatial and non-spatial data (Scholten and Stillwell, 1990; Yeh, 1999). This technology has been coupled with cellular automata model to simulate the dynamic spatial pattern of urban growth. This integration provides advantages over previously used approach such as the integration of GIS and statistical model, namely, multiple regression (Lodgson *et al.*, 1996; López *et al.*, 2001) and discriminant analysis (Narimah and Ruslan, 2001) or GIS and spatial interaction model (Clarke *et al.*, 1998; Scholten *et al.*, 1999), which were static and often required large amount of data (Lee, 1973; Narimah, 2002). A few studies have demonstrated that cellular automata and GIS can be used to simulate the historical spatial pattern of urban development (Clarke *et al.*, 1997; Clarke and Gaydos, 1998), plan and manage urban spatial growth (Wu and Webster, 1998; Engelen *et al.*, 1999; Yeh and Li, 2001). With the exception of studies undertaken in a few regions of China, however, most of these studies are conducted in relation to urban spatial growth of cities in the western developed nations, which experience a modest population growth. Thus, in order to evaluate cities in developing nations, a locally derived approach needs to be developed in order to understand and solve local urban problems.

THE CONCEPTUAL FRAMEWORK OF THE PROPOSED STUDY

The Formulation of the Proposed Model

The GIS-based CA model proposed for this study is developed using a 2-dimensional CA. The structure and concept of the model is given in Figure 1. This figure illustrates that the study area is divided into cell of 30m spatial resolutions. Each cell has five different states representing land use at the study area. It is given by:

$$\overset{t}{ui,j} = \begin{cases} 0 = \text{non - developed land} \\ 1 = \text{urban land} \\ 2 = \text{traditional village} \\ 3 = \text{wetland} \\ 4 = \text{forest reserve} \end{cases} \qquad (1)$$

"Non-developed land" includes all land that can be converted to other development activities. This includes agriculture areas, vacant land or shrub. "Urban land" is land that is already being utilized for urban activities such as residential, industrial, commercial and administrative or public facilities. "Traditional village" is defined as residential area outside built-up areas. "Wetland" is flood-prone area located near rivers within the study area. "Forest reserve" is area being identified in Seberang Perai Structure Plan to be protected from any development (SPMC, 1998).

The evolution of cells from time *t* to *t* + *1* is determined by a function of its state at time *t* and its neighbourhood space and a set of transition rule. The transition rule is formulated based on various criteria or factors that can influence urban development and the number of developed neighbours within a defined neighbourhood. Criteria influencing urban growth included physical, socio-economic, environment quality and amenities (Chapin and Kaiser, 1979; Ruslan, 1991; Narimah, 2002). Physical factors commonly used in the study of urban development are topography, soils and geology (Keifer, 1965; Narimah and Ruslan, 2001). For instance, area with 2 to 6 % slope is desirable for urban development (Urban Land Institute, 1991). Another important criterion that drives land use development is accessibility of sites to other supporting activities such as schools, health facilities, employment centres, and other developed areas (Chapin and Kaiser, 1979).

In order to evaluate the influence of each criterion on urban development, a Multi-Criteria Evaluation (MCE) approach is used. MCE is a process of combining data according to their important. It involves choosing a set of suitable sites for a certain objective based on a series of decision criteria and its relative weights (Eastman, 1999; Malcweski, 1999). In its simplest form, this approach can be stated as:

$$S_{i,j}^{t} = \sum_{i=1}^{m} x_{i,m} \cdot w_{m} \cdot \prod c_{m} \qquad (2)$$

where,

$S_{i,j}^{t}$ = suitability score for cell at row *i* and column *j* for urban development

$x_{i,m}$ = factor m that existed at cell at row *i* and column *j*

w_{m} = weight that represents relative important of factor m

c_{m} = constrain or factor m that hinder new development to occur

In addition to suitability score, the evolution of cells' states also depends on the number of developed cells within a defined neighbourhood. In many cases, the neighbourhood defined as a 3 × 3 cells or Moore neighbourhood (cells at the north, south, east, west, southwest, southeast, northwest and northeast) is used. Then, the model is formulated as a rule-based model using *IF*, *THEN*, and *ELSE* statements such that, for all vacant cells, their evolution from non-developed to developed is determined base on their suitability value $S_{i,j}^{t}$ and number of developed cells within a neighbourhood $\Omega_{i,j}^{t}$ (adjacency factor) such that,

$$\begin{array}{llll}
\text{For} & u_{i,j}^{t} = \text{vacant}; & & \\
& \text{IF} \; \left(S_{i,j}^{t} * \Omega_{i,j}^{t} \geq \text{threshold value} \right); & & \\
& \quad \text{Then} & u_{i,j}^{t+1} = & \text{urban}; \\
& \quad \text{Else} & u_{i,j}^{t+1} = & \text{non - urban.}
\end{array} \tag{3}$$

The model uses land use 1990 data as an initial state and simulates the spatial pattern of urban development until total developed land matches with projected total urban land 2010 as forecasted in the Seberang Perai Structure Plan, 1998.

The Evaluation of the Model

Model validation is an important component in model's development since it gives an indication on model's ability to simulate the spatial pattern of urban growth within a specific location (Chapin and Kaiser, 1979). In CA based spatial model, such validation should be undertaken since this approach was often being criticized as too simple to realistically simulate urban growth (Couclelis, 1985; Sander, 1996). The validation of this model was undertaken by comparing the simulated urban pattern 1998 and actual urban pattern 1998.

METHODOLOGY

Background of the Study Area

Seberang Perai is part of Penang state, which comprises of Penang Island and Seberang Perai in the mainland. It is located in the Northwest of Peninsular Malaysia. Figure 2 shows the location of the study area. Seberang Perai lies wholly in the tropic between 5° 5' 00" N and 5° 35' 00" N latitude with total area of 735 km^2. It extends from east to west longitude of 100° 20' 00" E and 100° 35' 00" E. Seberang Perai can be divided into three administrative districts: the northern district, the central district and the southern district. Geographically, this area is relatively flat and suitable for many development activities (SPMC, 1985).

Urban development in Seberang Perai was mainly due to industrialisation and spill-over demand form Penang Island. Its total population was 545,688 (Department of Statistics, 1991). Current planning policy and related population projection suggested that by 2010, this area would accommodate approximately 904,400 people (SPMC, 1998). In order to accommodate this population increase, another 16% of its total land would be required for other urban activities. Furthermore, current planning strategies were devised to direct more urban development into the Southern district, which were the least developed districts in the Seberang Perai region. Although current planning approach allowed planners to estimate the amount of land to be converted to urban, it did not allow planners to predict the spatial pattern of urban growth or evaluate the resulted urban pattern for such planning strategies. At present the spatial pattern of urban development in the Seberang Perai region could be characterised as a combination of an expansion of existing urban areas, a compact type of growth in the Northern District and dispersed urban development along major roads.

Database and Software Used in the Study

In order to develop a temporal dynamic spatial model of urban growth, various datasets representing physical and other supporting activities of the study area were needed. Digital land use data 1990 was obtained from Geography Section, Universiti Sains Malaysia and land use 1998 was obtained from Seberang Perai Municipal Council. Other data such as road network, railroad, slope, and public facilities such as schools and health clinics were extracted from topographic maps (Department of Survey and Mapping, 1986).

Arc/Info GIS software (ESRI Inc., 1994) was used to manage and to manipulate the required data and to develop the model. Functions used included distance and proximity analysis, reclassification, selection, map overlay, and calculation. All data that were gathered at different scale, sources and time periods, were standardised into the same raster format at 30 m resolutions using the Arc/Info GRID (ESRI Inc., 1994).

THE MODEL

The GIS-based CA model was developed using a tight coupling approach, which involved integrating GIS and spatial model normally by use of a macro language within GIS software. All data management and analysis were conducted using Arc/Info GRID and the model was developed using Arc Marco Language (AML) of Arc/Info (ESRI Inc., 1994). This process was relatively easy since model and data were manipulated within the same software. Proprietary GIS software was used in order to avoid heavy computational requirement, which was lacked among planners who would potentially used the model (Openshaw, 1978). First, the development of this model involved writing an AML scripting program to evaluate criteria influencing urban development and subsequently produced the suitability index maps. Then, another AML scripting program was written to simulate the spatial pattern of urban growth starting 1990 until the total number of urban area matched with total urban land predicted to occur in the Seberang Perai region at 2010 (SPMC, 1998)

As mention in Section 3.1, urban spatial growth in the study area could be describe as a compact and dispersed type of growth along major transport network. Thus, in order to simulate the spatial pattern of urban growth in this area, two development scenarios were tested namely a compact development scenario and a highway influenced development scenario. A compact development scenario only allowed new development to occur around existing urban areas. This scenario incorporated objective outline within the Structural Plan, intended to prevent urban development from scattering into agricultural land within urban fringe areas. The second scenario tested accounted for the influence of two major highways, the North-South Expressway and Butterworth-Kulim Expressway across the study area. These two highways provided better access between Penang port and other remote locations and were expected to channel urban development away from existing urban centres (Muller, 1995). These two highways, however, are tolled with access to and from them are limited to their intersections. Instead of promoting ribbon-like development along these highways, these infrastructures were expected to produce new urban pattern that were clustered near their intersection. Thus, a few new developments were automatically seeded near these intersections. Furthermore, these highways were also mapped and treated as one of the criteria that influence urban growth.

CRITERIA INFLUENCING URBAN DEVELOPMENT

The spatial pattern of urban growth was influenced by various criteria. The model proposed in this study intended to capture three sets of criteria; local, regional and global criteria. The local criteria described the physical characteristics of the cells, such as soil condition and topography. Regional criteria described the spatial relationship between cells and other functional activities within the study area. Finally, global criteria incorporated legislation, for example, the exclusion of paddy field agriculture from any development activities (SPMC, 1985).

These criteria were analysed using MCE in order to determine site suitability for urban development. Each criterion was assigned with its weight or relative important in influencing urban growth. Weights assignment within MCE studies is always subject to a certain degree of subjectivity as it relies on decision maker's opinion, knowledge or experience (Banai-Kashani, 1989; Collins, 2001). Thus, to realistically represent urban systems in the Seberang Perai region, weights were assigned on the basis of information gathered from literature review, planning documents and interviewed with local planners (Narimah, 2002). The weight for each criterion was derived by the use of a pairwise comparison approach, which involved comparing the relative importance of every pair of criteria. Tables 1 and 2 show pairwise comparison value assigned for all criteria used in a compact development scenario and a highway influenced development scenario, respectively. These tables illustrate criteria used in this study (rows) and their relative important compared to other criteria (columns). For example, from Table 1, it indicated that proximity to developed areas was three times more important than proximity to roads.

Table 1: Pairwise comparison assigned for each criterionused in a compact development scenario

riteria	Proximity to Roads	Proximity to Developed Areas	Proximity to Employment Centers	Proximity to Major Towns	Proximity to Schools	Proximity to Health Clinics
Proximity to Major Roads	1					
Proximity to Developed Areas	3	1				
Proximity to Employment Centers	3	3	1			
Proximity to Major Towns	2	3	1/3	1		
Proximity to Schools	1/2	1/3	1/4	1/5	1	
Proximity to Health Clinics	1/3	1/4	1/5	1/5	1/2	1

The value from these tables were then analyzed using Decision Criteria analysis within IDRISI GIS software (Eastman, 2001) in order to calculate weights for all criteria. Table 3 shows weights calculated for each criterion used in the study for the two-modelled scenarios. Two MCE-generated suitability maps were produced using these criteria and their weights (Figure 3). The most suitable areas for urban development were shown in black while unsuitable areas were shown in white. These maps were used in the simulation of each modelled scenario, where at each iteration the suitability maps were interactively recalculated to incorporate cells' suitability into the models.

Table 2: Pairwise comparison assigned for each criterion used in a highway influenced development scenario

Criteria	Proximity to Roads	Proximity to Major Towns	Proximity to Employment Centres	Proximity to Developed areas	Proximity to Schools	Proximity to Health Clinics	Proximity to Highway
Proximity to Major Roads	1						
Proximity to Major Towns	3	1					
Proximity to Employment Centre	4	2	1				
Proximity to Developed Areas	3	2	1/3	1			
Proximity to Schools	1/4	1/4	1/3	1/2	1		
Proximity to Health Clinics	1/4	1/5	1/4	1/3	1/2	1	
Proximity to Highway	4	3	2	3	4	5	1

Table 3: Criteria and their Weights used to produce MCE-suitability map to model the compact development scenario and a highway development scenario

Criteria	Weights Used for a Compact Development Scenario	Weights Used for a Highway Influence Scenario
Proximity to Highway	-	0.31
Proximity to Existing Developed Areas	0.16	0.14
Proximity to Major Roads	0.38	0.08
Proximity to Employment Centres	0.25	0.23
Proximity to Major Towns	0.10	0.14
Proximity to Schools	0.06	0.06
Proximity to Health Clinics	0.05	0.04
Consistency Ratio	***0.02***	***0.06***

EVALUATION OF SIMULATED URBAN GROWTH RESULTS

The resulted spatial pattern of urban growth was compared with actual urban areas in order to validate the model. The compact development scenario performed quite well with a total accuracy of 91.4%. However, the user's and producer's accuracy for urban category was only 78.6% and 76.0%, respectively (Table 4). The model assigned 21.2% (≈29.0 km^2) of urban land as being non-urban and 23.9% (≈33.8km^2) of non-developed land as being urban. The error of omission generated by this development scenario was due to its inability to recognize urban expansion in an anistropic manner and new development that was non-contiguous to existing urban areas (Narimah, 2002). The errors of commission occurred mainly as a result of non-urban land around existing urban areas being assigned as urban. On the basis of land suitability index, these areas might be suitable for urban development. However, there might be other factors that influence the spatial pattern of urban development that had not been assessed in this modelled scenario. For example, as noted by Yaakup (1991), land value played a significant role on urban development in Malaysia. This factor, however, had not been available for this study, and shall be considered in subsequent study.

Table 4: Validation results for the simulation of a compact development scenario between 1990 and 1998

Category	Actual Urban (km^2) 1998	Actual Non-Urban (km^2) 1998	Total (km^2)	Producer's Accuracy (%)
Simulated Urban (km^2) 1998	107.4	33.8	141.2	76.0
Simulated Non-Urban (km^2) 1998	29.0	562.3	591.3	95.1
Total (km^2)	136.4	596.1	732.5	
User's Accuracy (%)	78.6	94.3		

Total Accuracy: 91.4%

The second scenario investigated was a highway influence development scenario. Generally, the model performed better than the first modelled scenario with the user's and producer's accuracy for urban category was 80.9% and 78.5%, respectively. Table 5 shows the confusion matrix table produced for this scenario. Error of omission (19.1% or ≈26.1 km^2) was probably due to expansion of urban areas in an anistropic manner. The error of commission (i.e., non-urban being assigned as urban) is 21.5% (≈30.3 km^2) occurred at the edge of existing urban areas and infilling vacant land within the existing urban fabric (Narimah, 2002). The North-South Expressway runs across the existing urban centers, thus, not surprisingly, this modelled scenario performed well around major town of Butterworth and Bukit Mertajam. New developments that were seeded at the major highway intersections appeared to merge with existing urban areas. In the Southern District, however, this model seemed to overestimate urban expansion near Jawi and Nibong Tebal. Based on MCE-generated suitability map, these areas had potential to be developed. However, as noted by Morshidi *et al.*, (1999) and Mohd Bazid (2000) due to inequality among regions, these areas had not grow as rapid as other region within the study area.

Table 5: Validation results for the simulation of a highway influence development scenario between 1990 and 1998.

Category	Actual Urban (km^2) 1998	Actual Non-Urban (km^2) 1998	Total (km^2)	Producer's Accuracy (%)
Simulated Urban (km^2) 1998	110.4	30.3	140.7	78.5
Simulated Non-Urban (km^2) 1998	26.1	565.8	591.9	95.6
Total (km^2)	136.5	596.1	732.6	
User's Accuracy (%)	80.9	94.9		

Total Accuracy: 92.3%

DISCUSSION

In general, although the modelled scenarios perform quite well, the accuracy of the highway influenced development scenario was slightly better than the compact development scenario (by 2-3%). Assuming the transition rules and related MCE-suitability index derived for these scenarios were realistically parameterized, it could be concluded that current planning policies had produced urban growth that could be characterized by the expansion of existing urban areas. Furthermore, the spatial pattern of urban growth produced using these models were broadly similar.

The two scenarios evaluated were used to predict the spatial pattern of urban growth up to 2010. Figures 4 and 5 show the spatial pattern of urban growth produced using a compact development scenario and a highway influence development scenario respectively. It seemed that both of the scenarios evaluated tended to produce the spatial pattern of urban growth that were concentrated around existing urban areas. Furthermore, the inclusion of highway influence appeared to produce relatively few new urban centres, and only a little variation in the boundary morphology of urban areas that were likely to experience urban development (Narimah, 2002).

A GIS-based CA model developed in this study had a potential to become a mechanism for planners and urban managers to understand the spatial pattern of urban growth that were likely to occur resulted from the scenarios tested. For example, the result from this model illustrated that although policy makers intended to develop more land in the Southern district, it seemed that new urban development continued to concentrate around existing urban centres. The Southern district would continue to experience a linear type of growth along the road. This was probably due to a unique characteristic of urban growth in this area, which was termed 'desakota' region to describe the relationship between rural and urban region (McGee, 1967). This type of urban growth was resulted from industrialisation, where many factories were opened outside existing urban areas in order to have access to cheap land and abundant labour (Potter and Lloyd-Evans, 1998; Sui and Zeng, 2001). Second, planners could use this model to evaluate different planning programmes drafted in the Structural Plan within a computer environment prior to adopting specific plan for urban development. Such exercise could be undertaken by interactively seeded new development to act as a growth centre within selected areas and ran the simulation in order to evaluate the impact of injecting specific growth pole into the surrounding regions. This approach allowed planners to predict the impact of specific plan on the overall pattern of urban growth in the region.

CONCLUSION

On the whole, the study demonstrated that the application of a GIS-based CA model developed for the Seberang Perai region, Penang, Malaysia predicted the spatial pattern of urban growth with the accuracy of between 76% and 80%. This approach would potentially be useful for planners and policy makers to establish a methodology for evaluating and implementing spatial models in land use allocation. Such approach provided the functionality to test various planning theories and strategy in a controlled computer model prior to their implementations. This model also allowed planners to identify and map areas likely to experienced urban development, therefore, a cohesive planning strategy could be devised to manage and monitor urban growth. This model would be useful in planning and monitoring urban spatial growth, however, a further development in refining the transition rule would be needed in order to increase prediction accuracy of the model. This included incorporating socio-economic and economic criteria in the transition rule of the model.

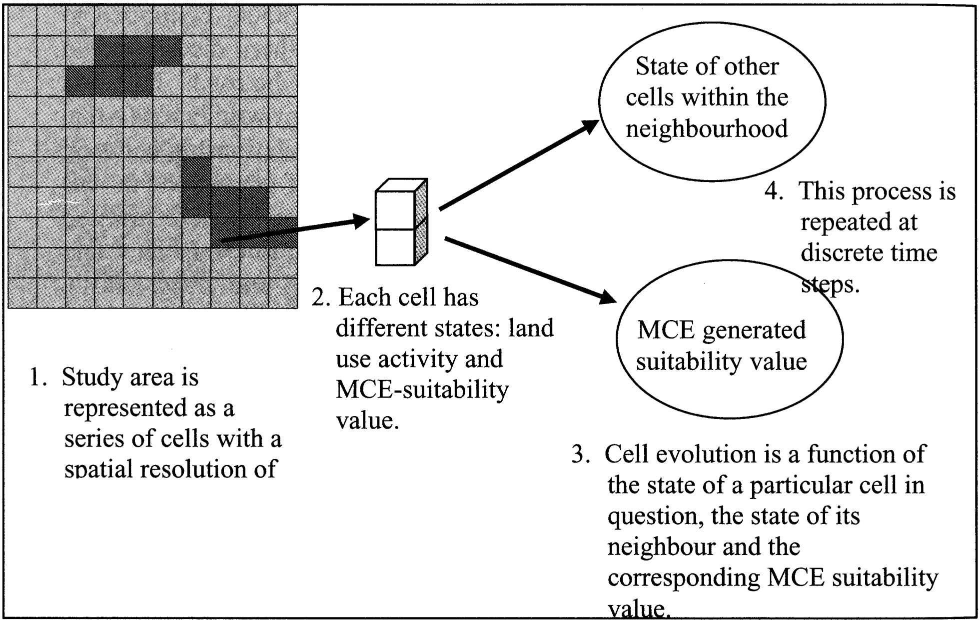


Figure 1: Structure and concept of the proposed GIS-based CA model (adapted from Coulthard, 1999).

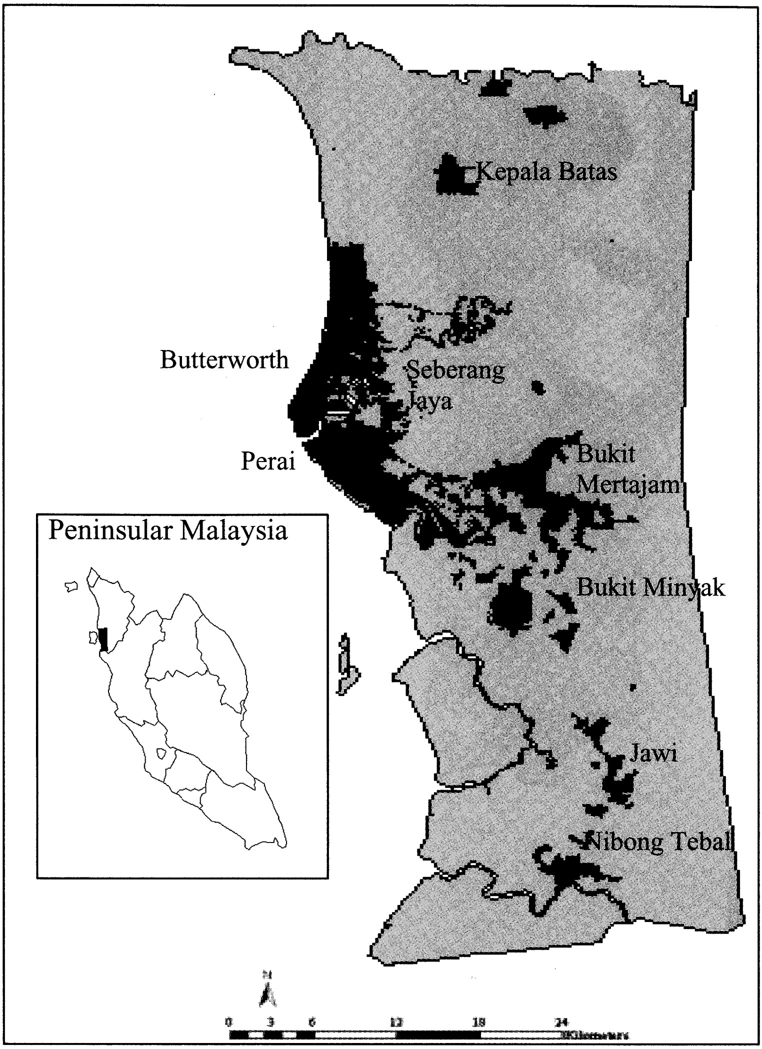


Figure 2: The location of the study area, major towns and urban areas 1990

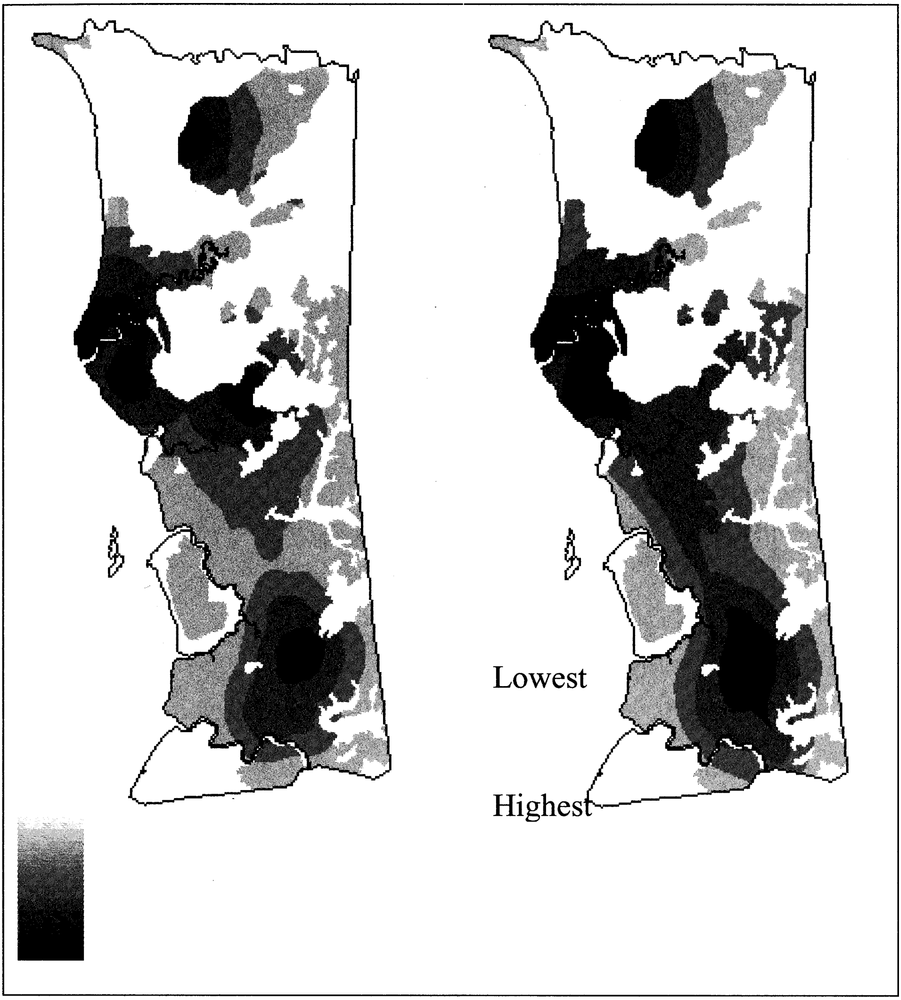
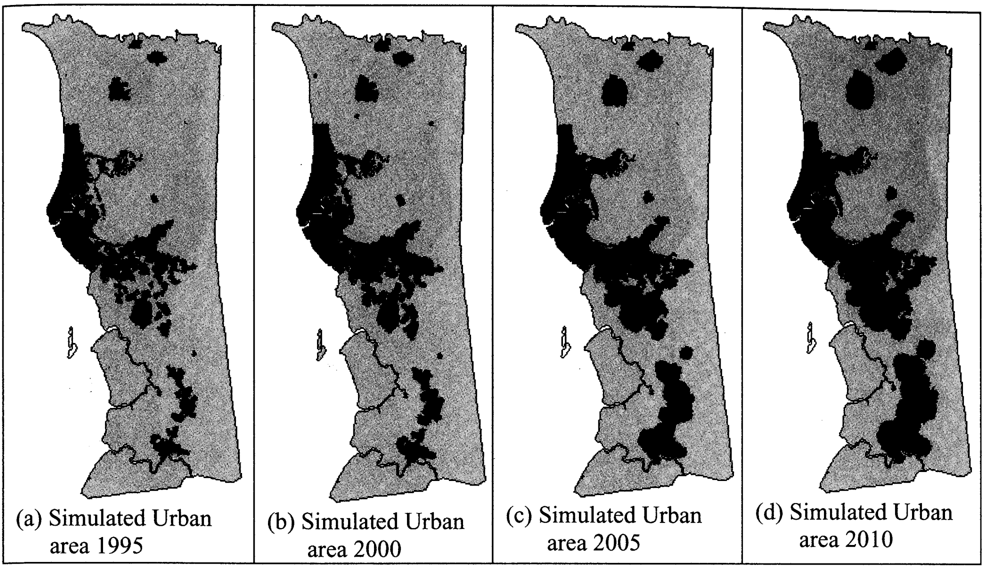


Figure 3: MCE-generated suitability maps used to develop a compact development scenario (left) and a highway development scenario (right)

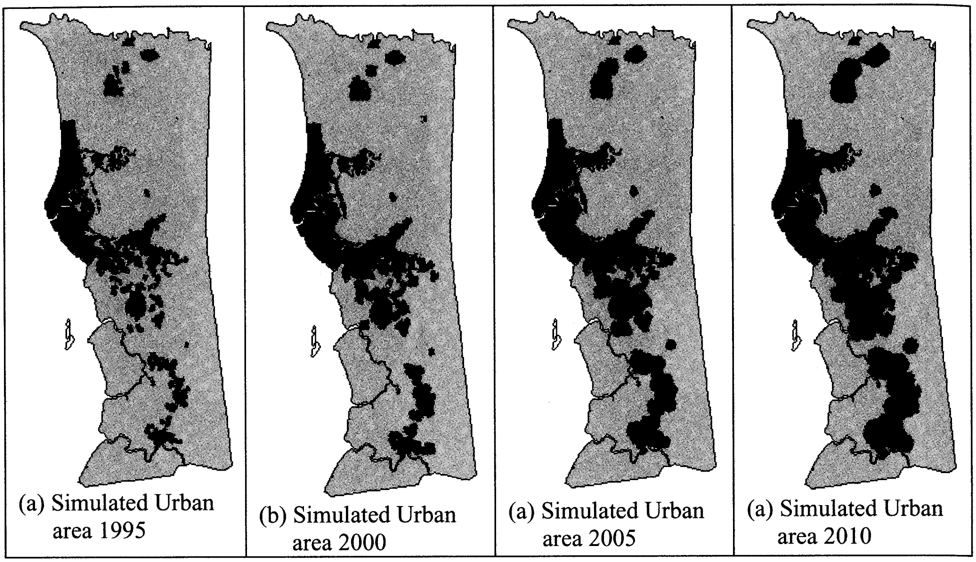

(a) Simulated Urban area 1995

(b) Simulated Urban area 2000

(c) Simulated Urban area 2005

(d) Simulated Urban area 2010

Figure 4: The simulated spatial pattern of urban growth produced using a compact development scenario



(a) Simulated Urban area 1995

(b) Simulated Urban area 2000

(a) Simulated Urban area 2005

(a) Simulated Urban area 2010

Figure 5: The simulated spatial pattern of urban growth produced using a highway influence development scenario

REFERENCES

1. Banai-Kashani, R., 1989, "A New Approach for Site Suitability Analysis: The Analytical Hierarchy Process", *Environmental Management,* 13(6): 685-693.

2. Batty, M. and Xie, Y., 1994, "From Cells to Cities", *Environment and Planning B: Planning and Design,* 21: S31-S48.

3. Batty, M., Couclelis, H. and Eichen, M., 1997, "Urban Systems as Cellular Automata", *Environment and Planning B: Planning and Design*, 24: 159-164.

4. Chapin, F.S. and Kaiser, E.J., 1979, *Urban Land Use Planning,* Urbana: University of Illinios Press.

5. Clarke, K.C., Hoppen, S. and Gaydos, L., 1997, "A Self-Modifying Cellular Automaton Model of Historical Urbanization in the San Francisco Bay Area", *Environment and Planning B: Planning and Design*, 24: 247-261.

6. Clarke, K. and Gaydos, L., 1998, "Loose-Coupling a Cellular Automaton Model and GIS: Long-Term Urban Growth Prediction for San Francisco and Washington/Baltimore", *International Journal of Geographical Information Science*, 12(7): 699-714.

7. Clarke, G., Langley, R. and Cardwell, W., 1998, "Empirical Applications of Dynamic Spatial Interaction Models", *Computers, Environment and Urban Systems*, 22(2): 157-184.

8. Chougill, C.L., 1994, "Crisis, Chaos, Crunch? Planning for Urban Growth in the Developing World", *Urban Studies*, 31(6): 935-945.

9. Collins, M.G., Steiner, F.R. and Rushman, M.J., 2001, "Land-Use Suitability Analysis in the United States: Historical Development and Promising Technological Achievements", *Environmental Management*, 28(5): 611-621.

10. Couclelis, H., 1985, "Cellular Worlds: A Framework for Modelling Micro-Macro Dynamics", *Environment and Planning A*, 1: 585-596.

11. Coulthard, T.J., 1999, *Modelling Upland Catchment Response to Holecene Environmental Change*, Ph.D. Thesis, University of Leeds.

12. Departmrnt of Statistics, Malaysia, 1991, *Population and Housing Report, Malaysia*. Kuala Lumpur, Malaysia: Department of Statistics Population Census Report.

13. Department of Statistics, Malaysia, 1996, *Urbanisation and Urban Growth in Malaysia*. Department of Statistics Population census monograph's series 1. Kuala Lumpur, Malaysia.

14. Department of Statistics, Malaysia, 2000, Laporan Kiraan Permulaan Banci Penduduk dan Perumahan [internet] available from http://www.statistics.gov.my/bahasa/prebanci2k.htm accessed 22 August 2001.

15. Department of Survey and Mapping, 1986, *Topographic Map*, Kuala Lumpur: Department of Survey and Mapping.

16. Devas, N. and Rakodi, C., 1993, "The Urban Challenge", in N. Devas and C. Rakodi (eds.), *Managing Fast Growing Cities: New Approaches to Urban Planning and Management in the Developing World*, London: Longman Scientific & Technical.

17. Eastman, J.R., 1999, "Multicriteria Evaluation and GIS", in Paul Longley, Michael Goodchild, David Maguire and David Rhind (eds.), *Geographic Information Systems: Management Issues and Applications*. 2nd edition. Chichester: John Wiley & Sons.

18. Eastman, J.R., 2001, *Idrisi 32 Release 2*, USA: Clark Labs.

19. Engelen, G., Geertman, S., Smits, P. and Wessels, C., 1999, "Dynamic GIS and Strategic Physical Planning Support: A Practical Application", in John Stillwell, Stan Geertman and Stan Openshaw (eds.), *Geographic Information and Planning*, London: Springer.

20. ESRI, 1994, *ARC/INFO Data Management*, California: Environmental Systems Research Institute Inc.

21. Goh Ban Lee, 1991, *Urban planning in Malaysia: History, Assumptions and Issues*, Kuala Lumpur: Tempo Publishing (M) Sdn Bhd.

22. Ibrahim Wahab and Abdul Hadi Harman Shah, 1992, *Kaedah Analisis Perancangan*. Kuala Lumpur: Dewan Bahasa dan Pustaka.

23. Kiefer, R.W., 1965, "Land Evaluation for Land Use Planning". *Building Science*, 1: 109-126.

24. Lee, C., 1973, *Models in Planning: An Introduction to the Use of Quantitative Models in Planning*, Oxford: Pergamon.

25. Lee Lik Meng and Tan T.S., 2002, "GIS for Plan Making in Penang Island: The Roads to Online Planning", *Online Planning Journal,* [Internet]. Available from: [<http://www.casa.ucl.ac.uk/planning/articles61/gispenang.pdf>] [Accessed: 29 June, 2002]].

26. Lodgson, M.G., Bell, E.J. and Westerlund, F.V., 1996, "Probability Mapping of Land Use Chane: A GIS Interface for Visualizing Transition Probabilities", *Computers, Environment and Urban Systems,* 20 (6): 389-398.

27. López, E., Bocco, G., Mendoza, M. and Duhau, E., 2001, "Predicting Land-Cover and Land-Use Change in the Urban Fringe: A Case in Morelia City, Mexico", *Landscape and Urban Planning*, 55: 271-285.

28. Malczewski, J., 1999, *GIS and Multicriteria Decision Analysis*, Chichester: John Wiley & Son, Inc.

29. McGee, T., 1967, *The Southeast Asian City*, London: G. Bell and Sons Ltd.

30. Mohd Bazid Kahar, 2000, *Personal Communication*, Penang Development Corporation.

31. Morshidi Sirat, Abdul Fatah Che Hamat, Abdul Rashid Abdul Aziz, Alip Rahim, Halim Salleh and Usman Yaakob, 1999, *Low-Cost Housing in Urban-Industrial Centres of Malaysia: Issues and Challenges*. Penang: Universiti Sains Malaysia.

32. Muller, P.O., 1995, "Transportation and Urban Form Stages in The Spatial Evolution of the American Metropolis", in Susan Hanson (ed.), *The Geography of Urban Transportation,* New York: The Guildford Press, 26-52.

33. Narimah Samat and Ruslan Rainis, 2001, "Integration of GIS and Statistical Technique to Model Urban Residential Land Use Development: A Case Study on Butterworth, Penang", *Malaysian Journal of Remote Sensing & GIS*, 2: 87- 98.

34. Narimah Samat, 2002, *A Geographic Information System and Cellular Automata Spatial Model of Urban Development for Penang State, Malaysia*, Ph.D. Thesis, University of Leeds.

35. Openshaw, S., 1978, *Using Model in Planning: A Practical Guide, Retailing and Planning,* United Kingdom: England Associates (Books).

36. Potter, R. and Lloyd-Evans, S., 1998, *The City in the Developing World,* United Kingdom: Longman.

37. Ruslan Rainis, 1991. *Linking Land Capability/Suitability Analysis with Environmental Models using Geographic Information Systems: An Iterative Modelling Approach,* Ph.D. Dissertation, The Ohio State University.

38. Sander L., 1996, "Dynamic Modelling of Urban Systems", in Manfred Fisher, Henk Scholten and David Unwin (eds.), *Spatial Analytical Perspectives on GIS,* London: Taylor and Francis, 229-244.

39. Scholten, H.J. and Stillwell, J., 1990, "Geographical Information Systems: The emerging Requirements, Henk Scholten and John Stillwell (eds.), *Geographical Information Systems for Urban and Regional Planning,* Berlin, Kluwer: Academic Publishers, 3-14.

40. Scholten, H.J., Van de Velde., Rietveld, P. and Hilferink, M., 1999, "Spatial Information Infrastructure for Scenario Planning: The Development of a Land Use Planner for Holland, in John Stillwell, Stan Geertman, and Stan Openshaw (eds.), *Geographical Information and Planning,* London: Springer, 12-134.

41. Seberang Perai Municipal Council, 1985, *Structure Plan (Draft),* Town and Country Planning Department, Malaysia.

42. Seberang Perai Municipal Council, 1993, *Structure Plan,* Town and Country Planning Department, Malaysia.

43. Seberang Perai Municipal Council., 1998, *Structure Plan (Reviewed),* Town and Country Planning Department, Malaysia.

44. Sui, D.Z. and Zeng, H. (2001) "Modelling the Dynamics of Landscape Structure in Asia's Emerging Desakota Regions: A Case Study in Shenzen", *Landscape and Urban Planning*, 53: 37-52.

45. Suriati Ghazali., 1999, *Socioeconomic changes in the peri urban villages in Penang, Malaysia,* Ph.D. Thesis, University of Leeds.

46. Tobler, W.R., 1979, "Cellular Geography", in S Gale and G. Olsson eds, *Philosophy in Geography*, Dordrecht, Hollond: D. Reidel Publishing Company, 379-386.

47. Torrens, P., 2000, "How Cellular Automata Models of Urban Systems Work: 1. Theory", *CASA Working Paper 28*, University of London.

48. United Nations Centers for Human Settlements, 1996, *An Urbanizing World: Global Report on Human Settlements,* Oxford: Oxford University Press.

49. Urban Land Institute, 1991, *Residential Development Handbook*, Washington D.C.: Community Builders Handbook Series, ULI.

50. Wu, F. and Webster, C.J., 1998, "Simulation of Land Development through the Integration of Cellular Automata and Multicriteria Evaluation", *Environment and Planning B: Planning and Design,* 25: 103-126.

51. Yaakup, A., 1991, *Application of Geographical Information Systems for Urban Planning and Management: A Case Study of Squatter Settlement Planning in Kuala Lumpur, Malaysia,* Ph.D. Thesis, University of Edinburgh.

52. Yeh, A.G-O., 1999, "Urban Planning and GIS", in Paul Longley, Michael Goodchild, David Maguire, and David Rhind (eds.), *Geographic Information Systems: Management Issues and Applications*, 2nd edition, New York: John Wiley & Sons, 877-888.

53. Yeh, A.G-O. and Li, X., 2001, "A Constrained CA Model for the Simulation and Planning of Sustainable Urban Forms using GIS", *Environment and Planning B: Planning and Design,* 28: 733-888.