R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 591–600.

MODELLING INFORMAL SETTLEMENTS USING A HYBRID AUTOMATA APPROACH

Faysal Kabir SHUVO and Patrick JANSSEN
National University of Singapore, Singapore
fkshuvo@yahoo.com, patrick@janssen.name

Abstract. Automata based modeling of urban environments focuses on the bottom up emergence of particular phenomena through interactions at the disaggregated level. Two popular approaches are *cellular automata* (CA) for modelling fixed automata and *agent based modelling* (ABM) for modelling mobile automata. However, certain urban phenomena cannot easily be modelled by either CA or ABM alone. This research focuses on one such phenomenon, referred to as *leapfrog development*, which is a discontinuous and dispersed type of urban growth. A hybrid automata model is proposed for modelling such phenomena that combines both CA and ABM into a single integrated model. The proposed model is demonstrated by applying it to a case-study in Dhaka city for simulating the growth of informal settlements associated with the readymade garment industry.

Keywords. Hybrid automata; GIS; agent based systems; cellular automata; informal settlements.

1. Introduction

Automata-based modelling of urban environments is a dynamic, bottom up, and disaggregated approach to modelling (Longley, 2005). Automata are the components within the model that process information and change the state of the system based on a set of transition rules (De Smith et al., 2007). Benenson and Torrens (2004) has formulated the automata as

$$\mathbf{A=} \{\mathbf{S,T}\};\ \mathbf{S=} \{S_1, S_2, S_3, ..., S_n\};\ \mathbf{T:} \{S_t, I_t\} \rightarrow S_{t+1}, \qquad (1)$$

where T is the set of transition rules, S_t is the state of the automaton at t time, I_t is the input information derived from neighboring automata, and S_{t+1} is the state of the automata process at time t+1.

Automata may be either fixed (such as a land parcel) or mobile (such as a pedestrian) (Benenson and Torrens, 2004; Batty, 2007). Two popular approaches to automata based modelling are cellular automata (CA) for fixed types of automata and agent based modelling (ABM) for mobile types of automata.

This research focuses on the modelling of the growth of the informal settlements within cities. Both CA and ABM models have been used for modelling this type of growth. Sietchiping (2004) and Hill and Lindner (2010) have developed CA models, while Barros (2004) and Vincent (2009) have developed ABM models. However, there is evidence that certain discontinuous and dispersed types of urban development, called *leapfrog development*, play a significant role in informal settlement growth. The concept of leapfrog development emerged from studies on the spatial evolution of urban areas (Benguigui et al., 2001). This type of development is by definition influenced by both local and global dynamic factors. For example, industries providing particular types of job opportunities may concentrate in certain areas of a city and influence the 'leapfrog' growth of informal settlement by pulling low-paid migrants worker away from outside of cities. Through this 'leapfrogging', informal settlements develop at specific locations within the city that are close to work locations and where there is favourable land in combination with other informal mechanisms.

Modelling using either CA or ABM alone cannot easily capture the dynamics of such leapfrog development since both fixed and mobile automata need to be considered. From an urban modelling perspective, there is little research that investigates both the local (at the settlement level) and global (on a city scale) pattern of such leapfrog type informal settlement growth. For such types of growth, it is argued that a hybrid model is required that combines CA and ABM.

In the field of urban or city modelling, the 'hybrid' term has been used at two levels. At one level, there have been attempts to integrate micro/meso scale models with macro-level models, where micro/meso scale models are provided as modular components for simulating various urban local dynamics (Torrens, 2001). At another level, the idea of 'hybrid' models have been seen as integrating fixed and mobile units of cities (Torrens and Nara, 2007; Wu and Silva, 2009). However, these hybrid approaches appeared to be insufficient as they do not fully integrate CA and ABM approaches into a single model.

The aim of this paper is to propose a hybrid automata model where both CA and ABM approaches are tightly coupled in order to be able to model leapfrog type informal settlement growth. The proposed hybrid model is applied to a case study in Dhaka, the capital city of Bangladesh.

2. Case Study

Rural to urban migration has been the dominant component of urban population growth (Islam 2006a; Alam and Rabbani 2007). The readymade garment (RMG) industry in Dhaka makes a significant contribution to the country's economic development, and the factories that have proliferated throughout the city have created a strong 'pull factor' for internal migration (Hoque et al., 2007). An estimated 300,000–400,000 migrants, mostly poor, arrive at the city annually (Rashid, 2009; World Bank, 2007). The workers in the RMG factories mostly come from this pool of migrants (Islam, 2006b; Mottaleb and Sonobe, 2011).

Despite the socio-economic importance of the RMG industry, the settlement issues of the factory workers have not been resolved, and as a result most workers will end up living in informal settlements. These settlements consist mainly of residential units made of fragile (kutcha) structure with one floor.

Unlike in other cities where informal settlements mainly develop at the urban periphery (Barros, 2004; Sietchiping, 2004), in Dhaka informal settlements have typically emerged within the city itself (Masum, 2009). Topological relations exist between informal settlement clusters and factory clusters. Figure 1 shows scattered pattern of informal settlements and factories.

The locations of the RMG factories strongly influence the location and pattern of the informal settlements. A reverse relationship can also be identified, whereby

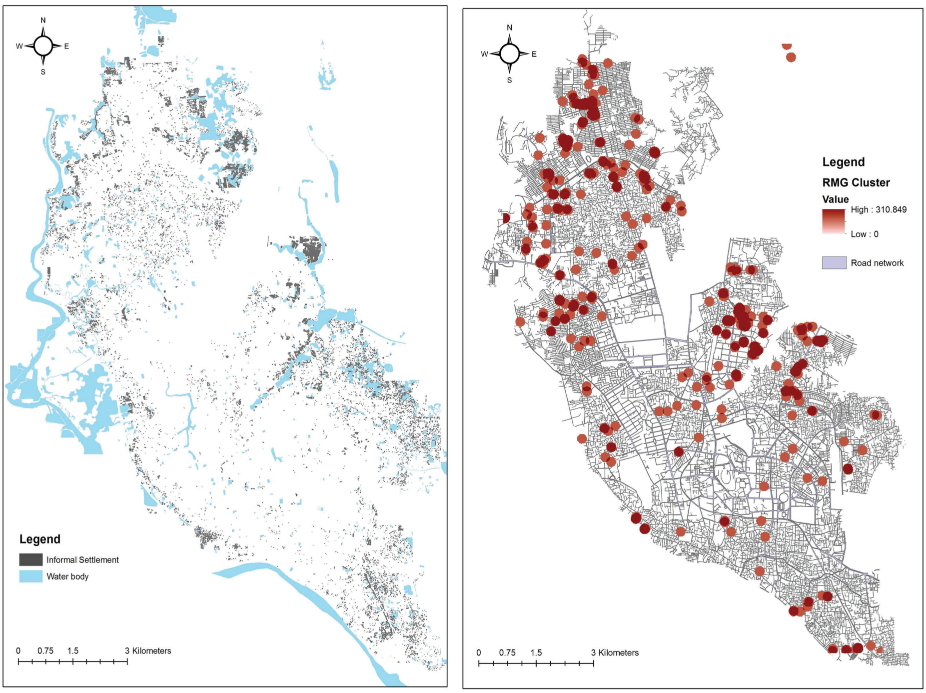

Figure 1. Scattered pattern of IS and RMG factories (black circle is industrial zone).

the location choice of factories is influenced by the locations of the informal settlements. In addition, Hoque et al. (2007) have found that most of the factories have been established besides main arterial roads and in buildings designed for other uses such as residential or commercial buildings.

2.1. HYPOTHESIS AND PROPOSED MODEL

Whenever there is a clustering of *RMG* factories, a clustering of informal settlements will also emerge. This clustering confluence leads to the development of non-homogenous patches of informal settlements around the city.

Based on analysis of existing land use data of the study area, it is hypothesized that a development pattern exists, whereby informal settlements at a particular location will grow up to a certain size limited by the constraints of the site and then leapfrog to a new location, where growth will again take place.

In order to test the validity of the leapfrog development hypothesis, a hybrid automata based model is proposed. In the proposed model, the factories and the workers are modelled as mobile automata, while the land units are modelled as fixed automata. The CA and the ABM are tightly coupled in a cyclical loop. The local suitability of parcels of land is modelled using CA while the location choice behaviour of the factory and worker agents is modelled using ABM. In each iteration of the loop, the CA is used to assign suitability scores for different activities to each land parcel and the agents in the ABM then make location choices based on these suitability scores. The conceptual framework is shown in Figure 2.

In order to reduce the complexity of the modelling task, this paper will focus only on the informal settlement dynamics (see the right hand side of Figure 2),

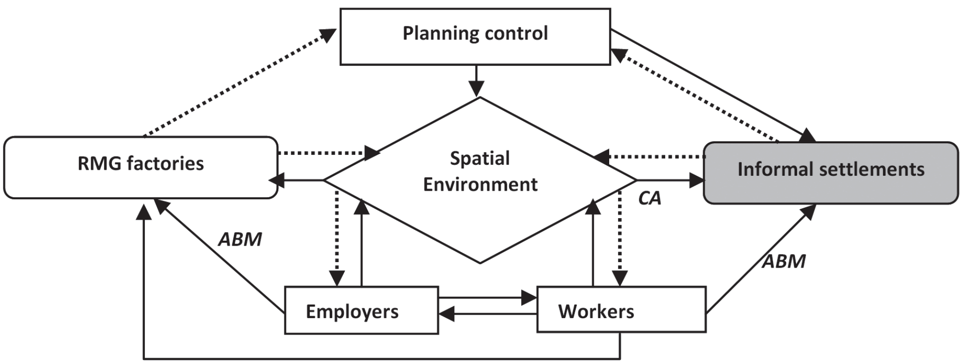

Figure 2. Conceptual framework of the hybrid automata model.2

including a CA for assigning suitability scores to parcels of land, and an ABM for modelling the worker location choices. RMG factories will therefore not be modelled as automata, but will instead be defined as static entities based on the time-series GIS data.

2.2. MODEL IMPLEMENTATION

For automata based models, time series data is required. From the detailed land-use data for the study area (e.g. construction year), the relevant data are sliced into three time series, for the years 1985, 1995, and 2005. The base year is selected as 1985 as this is considered to be the year when the RMG started to grow significantly.

The main aim is to demonstrate the validity of the leapfrog development pattern using a hybrid automata model. A hybrid model will be developed, and a set of transitional rules will be created for both the fixed and mobile automata. The temporal resolution or time step is considered one year. Starting from the 1985 dataset, the model will be run for 20 time steps in order to get a pattern of informal settlements for the years 1995 and 2005. The output generated by the model will then be compared to the actual datasets for 1995 and 2005.

The time-series data is created using ArcGIS, and the automata model is implemented in NetLogo, an integrated automata modelling environment. The shape file for the base year is first created in ArcGIS and then imported into NetLogo. The area of study is represented using a square cellular grid with a spatial resolution of two meters, where each grid cell is described as a *patch*. Each patch is assigned certain attributes that describe the patch. For example, a patch may be an RMG factory, an informal settlement, a water body, and so forth.

For informal settlements, patches are defined as being either habitable or non-habitable. For the 1985 data set, all patches in areas within the city that are vacant are assigned as being habitable. A habitable patch can be in one of three states: *empty* habitable patches have zero residents, *occupied* habitable patches have one resident, and *full* habitable patches have two residents.

The transition rules for the CA and the ABM are then defined based on these patches. The transition rules for the CA assign a suitability score to each habitable patch, and the transition rules for the ABM define how agents choose which habitable patch to settle on.

2.2.1. CA transition rules

The CA transition rules assign a suitability score to each habitable patch based on the local factors that are assumed to have influence on the workers' locational preference. These factors include proximity to RMG factories, proximity to existing informal settlements, presence of vacant public land and so forth. These factors are selected based on the analysis of the time series GIS data, field observation, and expert opinion.

The transition rules use two methods for describing the local conditions of a particular patch: the neighbourhood method and the distance method. The neighbourhood method examines the patches that are immediately adjacent to the current patch. In this case, the von Neumann neighbourhood is used, comprising the four patches orthogonally surrounding a central patch. The distance method examines patches further away, and uses a distance rule. The scoring system uses a scale from 10 to 1, where 10 indicates that the patch is highly suitable for informal settlement. The CA transition rules are shown in Table 1.

The above rules only apply to habitable patches. However, over time, patches may change their land use due to a variety of reasons. Such changes are land use type can be handled by special transition rules, referred to as *transformation rules.* In this version of the model, one set of transformation rules have been implemented to account for the phenomena whereby workers will create informal settlements directly adjacent to or over water bodies. Patches adjacent to or over water bodies can become habitable if all other habitable patches in the vicinity are full. Under these conditions, the pressure is deemed sufficiently high to result in informal settlements encroaching onto the water bodies. In future, transformation rules for other types of phenomena will be implemented, such as the

Table 1. CA Transition rules for habitable patches.

Rule Condition: RMG factories	**Rule Condition: Informal settlement**	**Rule Condition: Waterbody**	**Rule Result: Score**
Distance < 100 meter	Within neighborhood	Within neighborhood	10
Distance < 100 meter	Within neighborhood		9
Distance < 500 meter	Within neighborhood	Within neighborhood	8
Distance < 100 meter		Within neighborhood	7
Distance < 500 meter	Within neighborhood		6
Distance < 500 meter		Within neighborhood	5
Distance > 500 meter	Within neighborhood	Within neighborhood	4
Distance > 500 meter	Within neighborhood		3
Distance > 500 meter		Within neighborhood	2
		Within neighborhood	1

transformation of habitable patches to non-habitable due to the infrastructure construction projects such as road systems.

2.2.2. ABM transition rules

An ABM has been implemented to model the location choice of worker agents. For this demonstration, a very simple model is developed. In future, it is planned to elaborate this model in more detail.

The main source of settlement growth is due to new immigrants arriving in the city. Therefore, at each time step, a fixed number of worker agents are added to the city, and randomly assigned to work in the RMG factories in existence at that point in time. Though the annual immigrants are about 100,000, in this model the number of worker agents being added to the city is set to 2000 per year. Hypothetically, each working agent is considered to be equivalent to 5 persons in reality due to the system limitations of NetLogo.

Once the worker argents are assigned to factories, they then need to choose where they are going to settle. To facilitate this choice, the vacant and occupied habitable patches within a certain radius of the factory are first sorted according to their suitability score (as assigned by the CA). Each worker agent then selects the highest scoring available patch. Once they settle on a patch, the number of residents residing on that patch will be incremented by one. (Vacant patches become occupied, and occupied patches become full).

2.3. MODEL RESULTS

The hybrid model was run for a period of 20 years in yearly time steps, using the 1985 data set as a starting point. At five yearly intervals, visual maps of the simulation results were generated that show the extents of informal settlement growth. These simulated maps allow the gradual growth of the settlement to be better understood. The maps are shown in Figure 3.

For the final simulated 2005 map, the results are visually compared to the 2005 map showing the actual observed condition. It is found that there is significant similarity between the observed map and the predicted map.

Analysing the time series data in more detail reveals that older informal settlements tend to grow larger before new informal settlements appear at other locations. The simulated model produces similar patterns of growth. However, as a result of the input parameters, important differences between simulated and actual conditions can be seen. These differences are mainly due to the parameters for the ABM, such as the number of new workers per year entering the city. Future

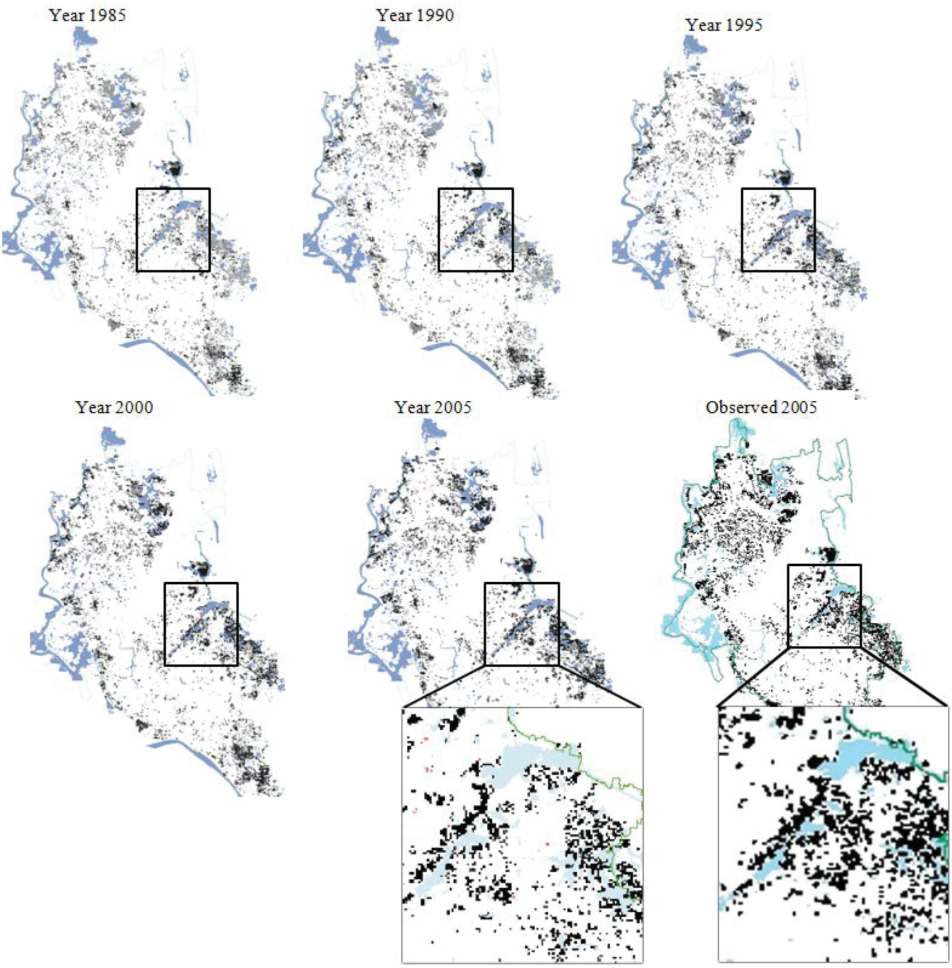

Figure 3. Comparison between the simulated and observed (last image) informal settlement patterns.

research will analyse historical and current data in order to define appropriate settings for these parameters.

3. Future Work

A hybrid model for leapfrog type urban growth has been proposed that tightly couples CA and ABM, thereby allowing both fixed and mobile automata approaches to be used. In the hybrid mode, the area of investigation is first split into a series of small land patches. A CA is used to model suitability of patches for certain activities, and an ABM is used to model location choices for agents engaging in these activities. The CA and ABM models are executed within a cyclical loop and affect one another through the data associated with the patches. The suitability scores generated by the CA will be used by the ABM, while the location choices generated by the ABM will be used by the CA.

The proposed hybrid model has been demonstrated by applying it to a case-study in Dhaka city for simulating the growth of informal settlements associated with RMG industries. Visual comparison of the actual and predicted maps showed significant similarity. These initial results suggest that the proposed hybrid model may be of value for simulating such leapfrog type urban growth.

The proposed hybrid model is in its early stages of development. Various types of sensitivity tests and validation processes are yet to be performed. A three phased validation process is proposed for this model, borrowed from Hill and Lindner (2010).

Acknowledgements

The authors are greatly thankful to NetLogo users community especially James F. Steiner, who voluntarily help on coding for the development of simulation. Also the authors would like to thank RAJUK (capital improvement authority of Dhaka) for providing GIS data of the Detailed Area Plan (DAP).

References

Alam, M. and Rabbani, M.: 2007, Vulnerabilities and responses to climate change for Dhaka. *Environment and Urbanization,* **19**, 81–90.

Ahmed, S. J., Bramley, G. and Dewan, A. M.: 2012, Exploratory growth analysis of a megacity through different spatial metrics: A case study on Dhaka, Bangladesh (1960-2005), *URISA,* **24**(1), 9–24.

Barros, J.: 2004, *Urban Growth in Latin American Cities: Exploring urban dynamics through agent-based simulation,* PhD Dissertation, Bartlett School of Graduate Studies of Architecture and Planning.

Batty, M.: 2007, *Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals*, The MIT press.

Benenson, I. and Torrens, P. M.: 2004, *Geosimulation: Automata-based modeling of urban phenomena*, Wiley.

Benguigui, L., Czamanski, D. and Marinov, M.: 2001, City growth as a leap-frogging process: an application to the Tel-Aviv metropolis, *Urban Studies*, **38**(10), 1819–1839.

De Smith, M. J., Goodchild, M. F. and Longley, P.: 2007, *Geospatial analysis: a comprehensive guide to principles, techniques and software tools*, Troubador Publishing.

Hill, A. and Lindner, C.: 2010, *Modelling informal urban growth under rapid urbanization: A CA based land-use simulation model for the city of Dar es Salam, Tanzania,* PhD Dissertation, TU Dortmund.

Hoque, D. M. S., Debnath, A. K. and Mahmud, S. M. S.: 2007, Impact of Garment Industries on Road Safety in Metropolitan Dhaka, *Proceedings of the Eastern Asia Society for Transportation Studies,* 2007.

Islam, N.: 2006a, Bangladesh, *in* B. Roberts and T. Kanaley (eds.), *Urbanization and sustainability in Asia: Case studies of good practice*, Asian Development Bank.

Islam, N.: 2006b, *Slums of urban Bangladesh: mapping and census, 2005,* United States Agency for International Development report.

Longley, P.: 2005, *Geographic information systems and science,* John Wiley.

Masum, F.: 2009, Urban Fringe Management and Role of Good Governance: Integrating Stakeholders in Land Management Process, *7th FIG Regional Conference,* Hanoi, Vietnam.

Mottaleb, K. A. and Sonobe, T.: 2011, An Inquiry into the Rapid Growth of the Garment Industry in Bangladesh, *Economic Development and Cultural Change*, **60**(1), 67–89.

Rashid, S. F.: 2009, Strategies to reduce exclusion among populations living in urban slum settlements in Bangladesh, *Journal of health, population, and nutrition*, **27**(4), 574–586.

Sietchiping, R.: 2004, *A geographic information systems and cellular automata-based model of informal settlement growth*, PhD Dissertation, The University of Melbourne.

Torrens, P. M.: 2001, *A hybrid geocomputation model for operational land-use and transport simulation*, Annual Association of American Geographers Meeting, New York.

Torrens, P. M. and Nara, A.: 2007, Modeling gentrification dynamics: A hybrid approach, *Computers, environment and urban systems*, **31**(3), 337–361.

Vincent, O. O.: 2009, Exploring spatial growth pattern of informal settlements through agent based simulation. MSc thesis, Utretch University; Delft University of Technology; Wageningen University; International Information for Geo-Information Science and Earth Observation.

World Bank: 2007, "Bangladesh-Dhaka: Improving Living Conditions for the Urban Poor". Available from: <https://openknowledge.worldbank.org/handle/10986/7686> (accessed on 6 December 2012).

Wu, N. and Silva, E. A.: 2009, "Integration of genetic agents and cellular automata for dynamic urban growth modelling". Available from: <http://www.biodiverse.unsw.edu.au/geocomputation/proceedings/PDF/Wu_and_Silva.pdf> (accessed on 6 December 2012).