



# Spatial Dynamic Models for Inclusive Cities: A Brief Concept of Cellular Automata (CA) and Agent-based model (ABM)<sup>1</sup>

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**Abstrak.** Kawasan perkotaan terutama di negara-negara berkembang menunjukkan laju pertumbuhan fisik yang tinggi. Telah banyak model yang mencoba merekonstruksi pertumbuhan perkotaan ini dengan menggunakan data demografi dan data sosial. Permodelan ini adalah salah satu yang lazim digunakan para praktisi perencana karena ketersediaan data dan waktu proses yang relatif lebih singkat. Sayangnya, model ini bersifat statis yaitu hanya menangkap karakteristik dan bentuk kota pada satu satuan waktu. Model ini tidak akan berubah saat variabel waktu berubah. Kebanyakan model ini bertujuan untuk memperkuat atau memperjelas suatu teori perencanaan perkotaan. Model statis ini juga memanfaatkan batas-batas administrasi dan tidak memungkinkan untuk melakukan permodelan di luar bentuk administrasi sebuah kota. Dengan permasalahan perkotaan yang semakin rumit yang menuntut pengambil keputusan membuat kebijakan tepat, diperlukan suatu metode permodelan pertumbuhan perkotaan yang dinamis yang dapat memberikan informasi yang lebih lengkap kepada pengambil kebijakan terkait struktur dan bentuk perkotaan, serta beroperasi pada skala yang lebih detail. Kemudian model perkotaan ini juga perlu mewakili perilaku para aktor pembangunan perkotaan. Salah satu konsep yang berkembang sejak tiga dasawarsa lalu adalah cellular automata (CA) dan agent-based urban model (ABM). Dalam konteks penelitian perkotaan di Indonesia, sayangnya konsep-konsep ini belum banyak tersedia pada jurnal-jurnal perkotaan dan terlebih lagi belum banyak kontribusi pada konsep-konsep permodelan dan mekanisme pada proses perubahan guna/tutupan lahan. Artikel ini bertujuan untuk memperkenalkan teori dasar CA dan adaptasi dari sistem tersebut untuk keperluan aplikasi di bidang spasial perkotaan. Kami juga akan menjelaskan konsep ABM sebagai komponen dari model yang memiliki kemampuan mewakili perilaku para pelaku pembangunan. Beberapa contoh aplikasi dan kemungkinan perkembangan model dinamis untuk kota inklusif akan diberikan di akhir artikel ini.

**Kata kunci.** Cellular automata, agent-based, permodelan perkotaan, Sistem Informasi Geografis

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**Abstract.** *Urban areas in the developing countries experience a rapid urban growth. Current practices in urban modelling employ demographic and social data as the inputs for urban models. These practices occur as a result of data scarcity in the developing countries. These models are static in which only captures the shapes of a city at the selected time. They have limitation in presenting the sequence of simulations over a series of time. Another limitation of static models is the use of administrative boundary as their unit of analysis, which often less accurate for large regions. When facing with a mounting complexity of a city, the decision makers need to obtain as much as information to guide their decisions. They need to know how big the magnitude of urban problems could have, and where exactly the policy should be implemented. They also need to know how different stakeholders influence the spaces in the cities. Cellular Automata (CA) and Agent-based Model (ABM) are the two prominent dynamic models occupying a large portion of spatial discussions in the last two decades. In the context of research in Indonesia, they are less recognized, and have less contribution to many urban applications. This article aims to briefly introduce the concept of CA and ABM in spatial context, in particular land use land cover changes in urban areas. Examples and potential application for inclusive cities are given in the last part of the discussion.*

**Keywords.** *Cellular automata, agent-based model, urban modelling, GIS*

## Introduction

One of the world phenomena in the 21<sup>st</sup> century is the booming population in the developing countries such in Asian and African countries (UNFPA, 2007). The UN (United Nation) predicted with the current 2012 population of 7.2 billion, a dramatic 2.4 billion people will be added to the world population to reach 9.6 billion by 2050 (UN-DESA, 2013); 40% of the future world population will emerge in the Asia's developing countries. Furthermore, nearly 50% (some authors suggest 80%) of this Asian population will live in urban areas; hereafter referred as urban population (Seto et al., 2012; UNFPA, 2007).

The growth of urban population demands spaces to support urban activities. Not only for housing, but also for pastures, growing crops, and spaces for infrastructures such as roads, schools, industries, and business centres. In the current situation, however, cities and urban areas in particular in Asian developing countries are having multi-dimensional issues ranging from inadequate provision of good quality housing, lacks of proper basic needs such as clean water, and issues of urban crimes and pollutions. But despite these problems, city has since a big magnet for rural population to come and venture their lives. It is without doubt, cities and its urban areas will be a major locus for what will be happening in the next decades, and managing the city greatly affects a wider part of people's lives.

Inclusive city is one of the core issues promoted by Asian Development Bank (ADB, 2011). It entails an “*economically, environmentally, and socially sustainable urban operations*” (ADB, 2011). Inclusive city aims to alleviate the adverse impacts of urban population growth and to address urban environmental issues to the entire urban population. In aiming this, one of the interventions in inclusive cities is to ensure a sustainable use of space, distributing equal urban services, and provision of infrastructure, to keep up with the human dynamic activities. Urban planning for cities in the developing world faces difficulties in envisaging the growth of a city and anticipating the necessary infrastructures for future urban population not only because lack of available and reliable spatial data but also on the loose nature of its spatial planning.

Spatial models have been helpful for urban planners in different stages of planning. Urban models have been used for visualizing the future growth of a city, simulating different types of scenarios on urban policies, or understanding the process of urbanization (Verburg et al., 2004). Urban models have the capability to account for the spatial changes of land uses/covers of a city and based on inputs that they received, predict the possible urban development according to the simulated scenarios. The theory and methods underlying urban models have been initiated and extensively developed in the United States and countries of West Europe since four decades ago.

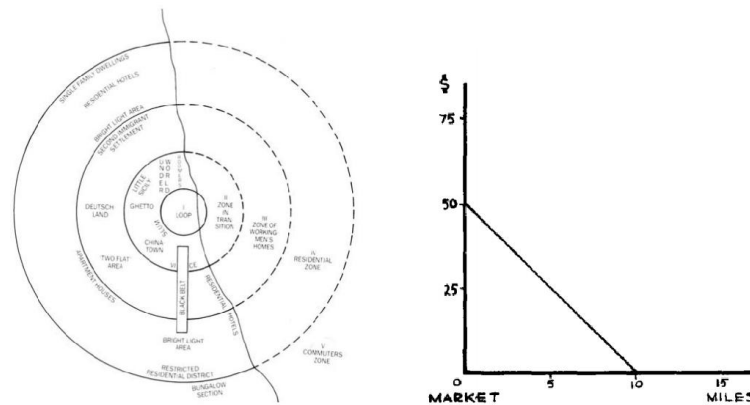
In accordance with the above reasoning, the aim of this paper is to introduce the concepts of urban models by explaining the two most prominent and emerging types of models in the last three decades. Urban models that adopt the cellular automata (CA) and agent-based models (ABM) concepts are the main focus on this paper. These two concepts of urban models are among the most discussed and emergence topic in the urban modelling literature. To achieve the aim of this paper, we present the basic concepts of CA and ABM without going too deep into a technical presentation. We try to keep the extent of the discussion on the general concepts and common procedures used in numerous urban models' applications, thus avoiding complex mathematical formulas. For readers who are interested with a more technical and detail discussion, a list of references will be provided as guidance for further sources. It is expected that this paper could promote more discussions on the concepts and applications of urban models with Asian cities' context and in Indonesia.

The following sections start with the introductory section on the urban planning concepts and the necessary for modelling. Section 3 discusses the CA urban model which then followed with explaining the ABM concept. Section 4 brings the future development of the urban models, and a conclusion.

## **Background**

As mentioned in the introduction, a city is a system (Wilson, 2000). As like other system, city has elements or sub-systems that constitute it. City has elements such as road, population, capital or economic functions; it has also transportation system, ecological system, social system etc. Within the sub-system, each part interacts with others. The interaction grows into a larger and more aggregated interaction between systems, and cross-scale between sub-system and system. All these interactions occur in a space. The interactions of these urban elements influence the configuration of spaces, but at the same time the spaces confine these interactions. To envisage the future growth of urban space, we need to understand the interaction between elements in the systems.

In a history of modelling, the spatial models always aim to understand how spaces are allocated and what mechanisms that shapes these spaces. Different types of models have been introduced since the beginning of 1960. Burgess' urban model captures the general features of Chicago by introducing multiple-ring that represents different functions of Chicago city (Wilson, 2000). Another model, is the land market theory by Alonso (1960) where he introduces the values of lands according to their distance from city centre.



**Figure 1.** The early urban model in 60's by Burgess (on the left side) representing a circular function of Chicago city and land values as observed from the distance of city centre by Alonso.

From a structural representation of functions in cities, in the 70 and 80's, urban models move towards a mathematical equation, in form of linear equations. The relation that links the factors and the possibility of urban areas to grow becomes more explicit. The parameters in the linear equation represent the weight that measures the strength of a factor on urban growths. To derive the weight in the mathematical equation various methods using historical pattern, Artificial Intelligence (AI), multi-criteria decision analysis, or Analytical Hierarchical Process (AHP) was used (Park et al., 2011). These urban models typically use data with the administrative boundary as the unit of analysis. This is mainly because the social and economy data come in the administrative boundaries. Population and demographic data were served by aggregating the information in single administrative boundary. The use of administrative boundary has limitation in that the detail information from the lower administrative regions is merged and smoothed out due to aggregation in the higher administrative regions. This is unfortunate because for spatial policies that need to be implemented within a region, these models are unable to supply the detail information. At the same time, these models are the most popular among urban practitioners because they save times and produce a sufficient simulation for policies in a regional level.

The third wave of urban models is during 90-00's. The evolution of urban models has been made possible along with the advancement of computer technology and a complex theory (Batty and Xie, 1994). The following section discusses the developments of urban models.

### Dynamic Urban Models

Why dynamic models? The challenge for urban planners in the 21<sup>st</sup> century is to try to understand the city better. This can be reached when urban planners obtain richer information on factors that influence land uses. They also need to know the disaggregated level of information from the models. Equally important is to know the possible shape, direction, and size of future urban development in a city to estimate the distribution of jobs, infrastructure, and population in the city. Static urban modelling gives the estimated urban growth on the specified time and has no capability in presenting the sequence transition of urban growth. The static modelling has limited capability in representing the influence of the surrounding neighbourhood in the urban development process.

This section highlights the relevant concepts in the dynamic urban growth modelling. Two prominent concepts presented here are: the cellular automata (CA) and Agent-based Modelling (ABM). These two concepts occupy a large portion of approach in urban modelling. The chapter starts with explanation on CA, the definition, its elements, how it works, and what are its limitations. The second part of the chapter discusses the ABM, what is ABM, a protocol in developing ABM, and critics surrounding the application of ABM for urban modelling.

### *Cellular Automata*

#### Introduction

Urban areas resemble a complex structure where various factors influence the dynamic of this structure. Urban areas can be continuous, clustered, ribbon-like features, scattered around the edge, or any combination of these patterns. Urban areas can be expanded or shrunk with time. All these patterns come from the micro-level phenomena where single land changes, and eventually emerge as an aggregate in global scale pattern.

The growth of where the spatial pattern that emerges from urban expansion is a product of various variables acting simultaneously creating an aggregate structure (Clarke and Gaydos, 1998). The structure is remarkably complex and difficult to be replicated using a simple mathematical rule with socio-demography data in a bounded administrative territory.

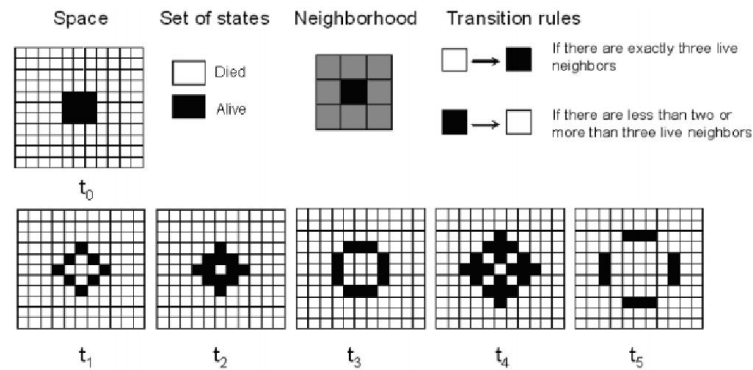
Understanding the small-scale phenomena in urban areas is therefore a key to model such complex pattern. It is the core idea in cellular biology, which later adopted in spatial research, where the growth of living cells constitutes the overall development of an organic system. An urban system can be seen as an organic system composed by small cells that can change its properties according to certain rules. The complex system of spatial system cannot be replicated by simple mathematical rule using ordinary regression with multiple variables. It can be approached by model that accounts for the micro interactions of the elements that constitute the system. In other words, the complex system of Cellular automata (CA) is a well-known tools in urban modelling (Batty and Xie, 1994; Clarke et al., 1997; Couclelis, 1997; Tobler, 1979; White and Engelen, 1993). It is a bottom up approach, which originally developed in computer programming by Wolfram (1983) and later in 90's was adopted by spatial researchers to study urban system. CA gains considerable attention among geographers and urban planners because it gives intuitive simulation results and delivers strong messages to its users. Urban growth (and shrink) can be easily simulated in CA, prompting its widespread uses for explaining urban dynamics (Jantz et al., 2004).

#### Element of CA

CA, in its conventional form, consists of four basic elements (Batty et al. 1997): (i) cell, (ii) state, (iii) transition rules, and (iv) neighbourhood (Figure 2) (Liu, 2008). The *cell* represents a spatial shape of CA. It carries the spatial properties of a cell and in its strict form has a square (lattice) shape. Indeed, the lattice is what makes CA can be smoothly implemented in the computer system. This is because a computer system performs better (less computation time) when the inputs are in a regular grid or in a matrix form.

The second element, the *state*, conveys the possible situation that a cell could have. In its most basic form, the state is a binary choice: dead or alive, active or inactive, or 0-1. The cell could

only have a single value at one time, but it can possibly change to another value according to the *transition rules* (see Figure 2).

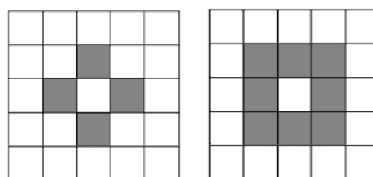


**Figure 2.** Element of cellular automata (CA) (top) with Conway's game of life as illustration (bottom) (Moreno, 2008).

Next, the *transition rules* determine the changing state of a cell. In other words, it is the element that decides how a cell can transform its state from one state to another. Again, in its strict form, the transition rules depend on the current state of neighbouring cells. Here below is the example of the transition rules with two states; non-urban (0) and urban (1), with Von Neumann neighbourhood (explained below).

*WHILE cell state is non-urban (0)*  
*IF the 3 or more Von Neumann neighbourhood are urban (1)*  
*THEN cell state changes into urban (1)*  
*WHILE cell state is urban (1)*  
*IF the 2 or more Von Neumann neighbourhood are non-urban (0)*  
*THEN cell state changes into non-urban (0)*

Neighbourhood is adjacent cells surrounding the centre cell. The neighbourhood cells are important because their states influence the next state of the cell in the centre. There are two types of neighbourhood in CA: the Von Neumann and Moore neighbourhood respectively represent the four and eight surrounding cells (see Figure 3).



**Figure 3.** Type of neighbouring cells in CA. The Von Neumann uses 4 cells shown on the left panel, whereas the Moore uses 8 cells on the right panel.

### Adaptation of CA for spatial studies

In the last two decades, the elements of CA have undergone a modification to adapt better in the spatial studies. In the study by Stevens et al. (2007), they proposed a cell that based on the residential parcels, departing from conventional regular grid form (lattice). Another example is Moreno (2008) that proposes housing parcels with non-uniform perimeters for a cell in CA. Parcel-based CA offers accuracy, as each parcel of house has spatial attributes that from it, decisions can be precisely be implemented. It however requires an accurate cadastral input which unfortunately often missing in the developing countries such as in Indonesia.

Another modification is on the state of CA. It has transformed from a binary state, into three or more states. The modification was necessary to accommodate ranges of land covers/uses that could have more than two classes. For example, land cover could have forests, bushes, bare lands, residential areas, or commercials states. If the modellers simplify land covers into two states for instance urban and non-urban, then at least between two states there should a graded transition between states. This gives the modification of states into a fuzzy state, explained more in Liu (2012).

Perhaps the most popular modification of CA is in the *transition rules*. The *transition rule* is considered to be the most important element in CA (Lau and Kam, 2005; Silva and Clarke, 2005). It is the core of CA with which CA able to simulate complex morphology of a city. With the notion that the transition in the state of the cell is influenced by various factors, the transition rule has been relaxed to accommodate more inputs; not just Von Neumann or Moore neighbourhood but any factors that influence the centre cell. This obviously attracts modellers to adopt various techniques and methods into CA through its transition rules. The most common adaptation in transition rules is the addition of spatial inputs such as slope, distance to road, distance to city centre, and so on as well as non-spatial data such as demand for housing, Gross Domestic Product (GDP) per capita (Wahyudi, 2013). Indeed, because CA can be seamlessly combined with various inputs and techniques, CA is currently regarded as a flexible tool in urban modelling (Sante et al., 2010).

### Examples of CA's applications in urban planning practices

Various applications of CA in urban planning have been reviewed in detail in Sante et al. (2010). Here, we depict few examples which by no mean covering the wide variant of application of CA. As CA has been adopted with many techniques, it carries different titles in the literature. For example, SLEUTH stands for Slope, Land use, Excluded, Urban areas, and Hillshade developed by Clarke and Gaydos (1998), was a CA model with a pre-determined input. It was considered as the early CA model, and still being developed with a large user community. It is a simple yet powerful model in mirroring types of development such as ribbon, leap frogged development, or natural spread.

In Europe, MOLAND is a CA model developed by a group of spatial researchers led by Engelen et al. (2007). Apart from spatial data input, it requires zoning status and socio-economic characteristic as its inputs. It has been tested mainly in cities in Europe such as Greater Dublin Area, Alpine corridor, and Algarve, Portugal (Petrov et al., 2009). For the latter, CA MOLAND was used to demonstrate the influence of touristic activities in Algarve to the growth of urban areas.

In the developing regions, CA has been implemented in cities with rapid urban growth such in Seberang Perai, Malaysia; Kathmandu, Nepal; Guangzhou, China (Naimah et al., 2011; Thapa and Murayama, 2012; Wu and Webster, 1998). The difference of CA models in these regions compared to the models in the developed region is on the factors that influence the urban growth. In the developing regions, area's proximity to roads and Foreign Direct Investment (FDI) are the two factors that strongly influence the urban growth. The use of these factors is typical in urban model in the developing countries where the quality of public transportation is poor and the number of workers is abundant. Another difference is on the types of land use that constitutes the urban growth. In the developing countries, the expansion of urban area is mainly composed (>70 percent) by informal settlement such as kampong or favelas, in contrast to formal, well planned residential, and industrial areas in the developed countries. It is in this context, that social issue such as housing supply-demand mismatch, gated community, and unequal distributed jobs opportunity likely to emerge in the developing region's context. In the next dynamic modelling approach i.e. Agent-based modelling (ABM), the issues of social and human behaviour aspect will be incorporated in the model.

#### CA limitation in urban modelling

Application of CA in urban modelling suits best for replicating urban morphology (Clarke et al., 1997; White and Engelen, 1993), but has limitation in exposing the connection and mechanism between the elements of spatial system (Benenson, 1999).

This limitation roots from its neighbourhood concept. In CA, the changing state of a cell is determined by the adjacent cells whilst the influence of distance objects for example on the distant influence of a city centre, is weakly represented. An absent concept of CA in explaining the distant object bring a relaxation on its formal neighbourhood concept by including the influence of distant objects using attraction -repulsion function or decay function (White and Engelen, 1993). Yet, these relaxations can be seen as an *ad-hoc* technique where it works in a particular case and has a weak theoretical basis. It is therefore, there is a need to adopt a sound method to systematically explore and represent the spatial pattern and spatial connection between spatial objects in CA model.

In addition to the limitation above, the concept of CA, which treats urban system as living organism, is inaccurate. Unlike living organism where cell is able to move or change its shape by itself (endogenous), urban system requires external stimulation to alter the shape of urban areas (O'Sullivan and Torrens, 2001). In the spatial context, the development of urban areas not only depends on various physical and socio-economy factors but the prime cause of the dynamics is the human. Actors in urban system such as developers, farmers, land owners, are the one who play the main role through their relationship in changing the lands which eventually emerge as large scale urban pattern (Benenson, 1999). On the actual process of urban growths, actors in urban system make their spatial decision based on the expected economic benefit (Benenson, 1999; Irwin and Geoghegan, 2001). The concept of CA, however, lacks of capability in representing the actors and their behaviour in urban system.

#### *Agent-based Models (ABM)*

This section aims to synthesize the elements, the benefits and the limitations of ABM as a tool in spatial model. It starts with the introduction that explains the core elements of ABM, and followed with the applications in urban planning. Next, a protocol commonly applied when constructing ABM is presented. A handful of software for simulation in ABM is presented. The



section continues with critics on ABM that – like other spatial models – has limitations for spatial studies.

### Elements of ABM

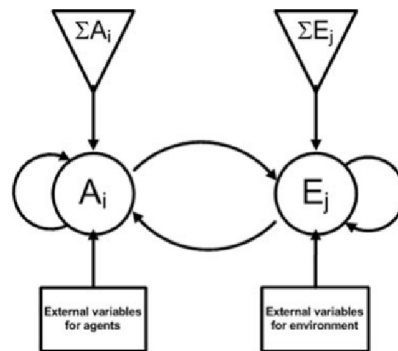
ABM can be defined as a combination of three elements: the agent, environment, and interaction. The agent in ABM is anything, which has a discrete entity with a distinct goal. Agent has autonomous behaviour which means it can change its behaviour in adapting to its surrounding (Crooks and Heppenstall, 2012). In urban system, agents can be animated or unanimated (Crooks and Heppenstall, 2012). The example of an animated agent can be a human which play a role as a residential developer, whereas the unanimated agent can be a land parcel (Parker, 2005). In a latter case, the unanimated agent carries a function as in CA model. Indeed, ABM can be seen as CA with additional functionalities (Torrens and Benenson, 2005). Cell in CA can be considered as the representation of agent without spatial movement. What makes ABM different from CA is that ABM allows the agent to roam in spaces whereas in CA, the cell (agent) remains in a fixed spatial coordinate (Crooks and Heppenstall, 2012).

The second element of ABM – environment –, is the location where agent performs its tasks. *Environment* represents the spaces in which spatial parameters attach to it (Crooks and Heppenstall, 2012). Geometrical values such as cell size, width, length, are examples of the parameters in the *environment*. The representation of space in ABM can be in various dimension, but generally in 2-dimension (flat space) with uniform grid space or – in a less common case- non-uniform as in land parcels (Moreno et al., 2008).

Depending on the objective of developing the model, using uniform grid space (cell) in the *environment* could offer more benefit than when using a non-uniform space. The most important benefit is the natural connection of cell with the computer process in which cell is treated as 2-dimensional array in computer which resulted in a faster time processing. But because the cell has to represent the most homogeneous state of reality, the cell in ABM's space naturally exhibit some errors. The modellers should be aware that in reality, spatial objects contain heterogeneity in a space of single cell/grid. Thus, the cell in ABM's space contains already a certain degree of uncertainty; in particular at the edge of the cell.

In ABM, the agent and environment interact towards themselves and towards each other's (Figure 4). This brings us to the third and the most important element of ABM; the *interaction*. The interaction is the main element of ABM that stands differently from the other modelling tools, such as the one using social-economy or mathematical approaches. There are mainly two kinds of interaction in ABM; agent-to-agents, and agent-to-environment interaction. The interaction is schematized in Figure 4 below. Denoted with A, the agent influences the Environment (E) by changing the state of the cell in the Environment, for example, by converting the cell from a non-urban state into urban. Likewise, the changing state of environment influences the agent, for example, knowing that a cell has been changed into urban, the agent which interested to build an urban spaces withdraws its decision to occupy the current cell and move onto the other cells (Matthews et al., 2007). In the agent-to-agent interaction, the interaction can be simply in the form of query; gathering information from other agents. Query or obtaining information for the agent from other agents holds the most basic interaction in ABM. Perceiving what others agent doing regarding their interest to certain land, gives crucial information for the agent to decide what he should adapt in his behaviour for the next step. Another type of interaction could be a *what-if* type of interaction, a typical scenario that the model adopts. In a higher level of complexity, the interaction includes the feedback

mechanisms; a changing behaviour of the agent in adaptation to such feedbacks (Fontaine and Rounsevell, 2009). This high level interaction was demonstrated in Vancheri et al. (2008) which includes construction process, occupation, construction and occupation, and conversion in the model.



**Figure 4.** Concept of ABM after Baynes (2009).

#### Applications of ABM in urban planning practices

ABM has been applied in various field studies encompassing spatial and non-spatial problems (see for example Epstein and Axtell, 1996; Filatova et al., 2009; Grimm et al., 2005; Matthews et al., 2007; Parker and Filatova, 2008). Focusing on the spatial science, Matthews et al. (2007) present a historical review of the applications of ABM in land use models. He classify the applications of ABM into (i) policy analysis and planning, (ii) participatory modelling, (iii) testing hypotheses of land use pattern, (iv) testing social-economy concept, and (v) modelling landscape functions. He further argues that despite numerous applications have been reported, they are largely sit within the research context, and never been fully implemented in the urban management policies. This is because the main advantage of ABM is in the informing stage. It uses as an avenue for “exploring” and “explaining” the hidden phenomena, and less suitable for the decision analysis. Another review of applications is by Parker et al. (2003). They offer a wider scope of review of Land Use Land Cover Change (LULCC) models in spatial applications. They start with the history of approaches in urban model; from early development of the model with a mathematical equation using single method, into a cellular approach and a combination of methods. They further break down the applications into (i) natural-resources management, (ii) agricultural economics, (iii) archaeology, and (iv) urban simulation. At the end of their article, they give an optimism of the multitude-possibilities of application of ABM in the future.

Here, we present two examples of the spatial model using ABM. The first, Loibl and Toetzer (2003) investigated the residential growths in Vienna’s suburban area. They found the simulation on the areas gives more realistic results when migration patterns of the population were taken into account. The migration patterns were translated into a spatial movement that suited best with the concept of animated agents in ABM. Another example was the organic settlements in Arab sub-urban in Israel, where *patriarchy culture* –a system in which the father has authoritative decisions among other family members– exists in the Arab community and was successfully simulated using ABM to better understanding the morphological expansion of urban areas in this village (Fisher-Gewirtzman and Blumenfeld-Liberthal, 2012). These two

applications stress the importance of agents' behaviour in the spatial model. Not only will it improve the simulation to be a more realistic, but also extend our understanding about the underlying process in urban system.

In the Asian and developing world context, the example of urban modelling with agent-based approach is fewer than that of the developed countries (Wahyudi, 2013). From these few examples, two studies are worth to be briefly presented here. The first study by Xie et al. (2007) investigates the *desakota* phenomenon in Suzhou-Wuxian region, China. The study presents an example of combination between CA approach and ABM. The *desakota* phenomenon changes the rural land cover into urban, but at the same time, transforms the rural households into urban lifestyles. To explain the expansion of urban areas toward city's peripheries, and adding an understanding about the process underlying the urban expansion, the ABM was implemented to represent the interaction between local developer's agents and the municipalities. The second study by Zhang et al. (2010) illustrates the role of agent-based approach in fostering understanding around the pattern and process link in the urban growth in Changsa, China. The interaction of a macro spatial policy imposed by the government, with a micro-spatial strategy played by the peasant and the residents leads to the expansion of urban growth in Changsa. This interwoven type of interaction with the heterogeneous development actors in urban system can be well-represented in agent-based modelling.

#### Protocol in ABM

The standard protocol in building ABM helps modellers to systematically conceptualize the model. It is not obligatory but it useful for the current (and future) users and a wider community of modellers to understand the overall aim of the model and the various components of the model that build it. Furthermore, building ABM by following the protocol allows subsequent development by modellers who are not necessarily related with the original models. One of the standards largely covers the main elements in ABM and has been adopted in ABM modellers' community is ODD developed by Grimm et al. (2006). ODD stands for Overview, Detail, and Design. It is a standard protocol for ABM in various applications; not necessarily spatial studies. The protocol obliges the modellers to start building the model with a systematic order from defining the objective of the model, until deciding the components of the models. ODD protocol in ABM guides the development of a model which is robust, sound, and easy to be compared with other ABM models. ODD protocol is a model's skeleton in that it explains the main structures that build ABM. It can quickly give an idea to the readers about the purpose and overall elements in the model (Grimm et al., 2006). The protocol consists of seven items which are described in Table 1.

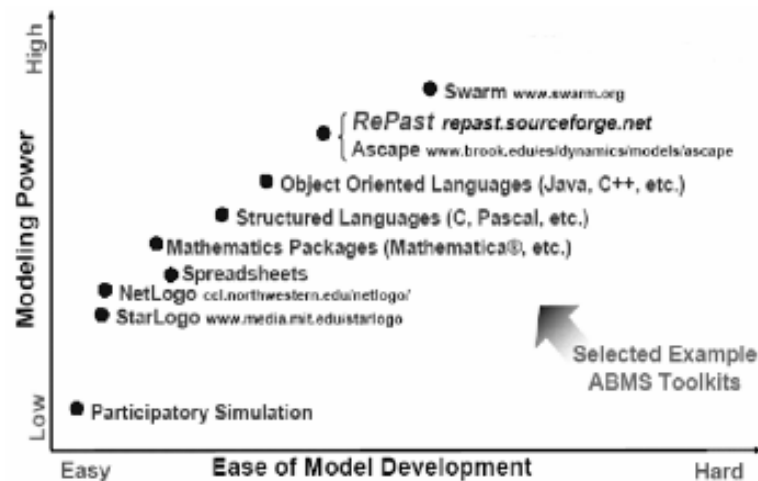
The definitions of the elements in ODD may not be self-explanatory and can be vague for some users and modellers in their early learning stage, but here we can argue that at the moment, ODD offers a simpler protocol without losing the generality for various ABM variants and applications. The main benefit of ODD would be the improvement of communication between the modellers and the users (or readers). The users, who possibly have less knowledge in modelling in particular ABM, have the opportunity to explore the model with a plain language rather than have to struggle understanding mathematical equations or pseudo codes which demand basic knowledge or at least familiarity with the advanced computer languages implemented by ABM.

**Table 1.** The seven elements of ODD protocol (Grimm et al., 2006) with example on the right panel

ODD protocol			EXAMPLE (adapted from Wahyudi, 2014)
<b>Overview</b>	Purpose	What the modellers want to achieve by building the ABM.	To develop a prototype of ABM featuring single agent with simple behaviour of having only one input (locational preference based on land prices). The overall aim is to ensure if the model works as it was aimed for as in the conceptual framework.
	State variables and scales	What is the most disaggregated variables in the system, and to which scale (spatial-temporal) the model will be built.	Agents: Developer (D), Resident (R), Government (G). D's state: type of developers (housing), land acquisition (ha), R's state: age, income, house preferred size, G's state: planning authorities in JMA, Spatial scope: Jakarta, 30m resolution, regional planning scale. Time scale: each run equals to one year; simulation ends after 15 runs (15 years).
	Process overview and scheduling	The basic processes which will run in the model. Explanation on the sequence of processes in the model.	Each agent has its own conceptual framework (CF) independent to others' CF. Agent has no influence to others agent. Agent looks for lands according to its financial capability and land prices.
<b>Design concepts</b>	Design concepts	The expected simulation results, e.g. emergence, adaptation, sensing, Stochasticity etc.	<i>Emergence</i> : The urban growths emerge from the behaviour of agent, <i>Stochasticity</i> : parameters in the model are treated as probabilities.
<b>Details</b>	Initialization	What is the situation of environment, agent, and other elements at the start?	Land use state resembles land use in the year 2000, Single agent every run. One agent in one model.
	Input	A dynamic state of variables, which drives the changing condition of environment over space and time.	Urban growth rate ( $u(t_i)$ ) changes from previous run ( $u(t_{i-1})$ ). Affected non-urban lands decrease on each run. Land prices increase every year (natural increase), in addition, the impacted/developed lands get a higher increase in land prices.
	Sub-models	Mathematical skeleton of the model.	Land searching will be formalised using normalised random and existing spatial pattern from the depiction of land prices on available reports.

### Computer software ABM

Without doubt the power of modelling in urban applications in the last two decades relies on the advancement of computer technology. In parallel with a more powerful computing ability, urban modelling becomes a more complex analysis involving larger data input, higher dimensional equation which need to be optimised, and a more dynamic visualization. All these advancements have to be paid with a high requirement of computer skill for urban practitioners. Even for practitioners who have basic understanding in computer programming, this could be a steep learning curve. Fortunately, various ABM software with different level of difficulties are available.



**Figure 5.** Depiction of various ABM programme currently available for urban modellers (North. et. al 2005 in Crooks (2006))

A selection of software currently used in various ABM urban modelling is shown in **Figure 5**. The x-axis represents an increasing modelling skill whilst higher modelling power in y-axis. StarLogo in the left-down of the diagram offers a basic function of ABM with user-friendly GUI (Graphical User Interface), whereas for software in the top-right of diagram offer flexibility and an advanced function which requires a high command in computer language. Repast and Swarm for example, are highly powerful software for spatial applications which involve larger areas and agents with complex interactions. In a general practice of ABM, most modellers would start prototyping their model in StarLogo or NetLogo then expands the complexity of the model in the Repast or more advanced software. For further literature on how to design and build agent-based models, Abdou et al. (2012) provides an extended discussion.

### Critics on ABM for urban land use

The applications of ABM in spatial context are not without critics. ABMs have been criticised because the modellers tend to overly design the elements of ABM; the agent and its environment to mimic the reality (Couclelis, 2001). This practice tends to over-fit the parameters of the models and creates *unrealistic assumptions* which at the end detached the models from the reality. This common situation happens when the modellers start to build the behaviour (or properties) of the agent which will react to specific target environment. As like others model, ABM represents only a tiny windows of reality that from it, the modellers have to draw lessons. The modellers should not trying to replicate the reality as their objective but rather

aim to understand the mechanism between the components in the system that influence the overall structure of the system. The configuration of a city and urban areas are important, but in ABM, the main aim is to expose the relation between components that initially hidden which then emerges through the micro-simulation of the interaction between agents and environment; thus it is misleading to target the exact shape of the city through ABM. For further reading, we suggest reader to read Couclelis (2001).

### **Conclusions and Discussions**

The micro-scale, fine arrangement of urban areas is considered too expensive to be undertaken using conventional spatial models. The advancement of computer technology and complex theory made recreation of urban growth from micro interaction possible. CA and ABM are promising tools for urban models as they suit best for city that works similar to a complex system. This paper explains the concepts and elements of CA and ABM. CA is a concept that suits best to represent the shapes (fabric) of a city; the ribbon, leap frog, natural development, whereas ABM suits best with cases where the interaction of actors involved in urban system are more than one way and actors have complex behaviour including learning and adaptation (Bonabeau, 2002). Like many other models however, both concepts have limitations with one of them is over-fitting the reality. Proper implementation of CA and ABM using conceptual framework and ODD protocol helps the model to improve its openness and reach its objective.

In regards to inclusive cities where economic opportunities and quality of life for all citizens are the objective, urban models in general, helps the decision makers to foresee the possible urban growths. But the adoption of dynamic urban models such as CA and ABM in urban model add new dimension in which modellers understand about the urban system, the elements, and the interactions of the elements of modellers. CA and ABM open the possibility for modellers to learn from the configuration and shapes of the cities that emerge from the simulations. Social segregations, the sprawl of middle-higher dwellings, and unequal services of infrastructures, are among the examples of problems that emerge from the simulation of urban growths. Decision makers who fought for inclusivity, could anticipate these emerging urban problems from using CA or ABM urban models.

Various concepts and combination of urban models have been demonstrated in numerous cities in developed regions. In Asian countries however, the discussions on concepts, methods, and application of urban models with Asian context - typified with potential population booming and complex urban planning issues - are scarce. There are few urban modelling literatures both in the description of the methods and the application in the developing world context. This paper should be regarded as an initial attempt in disseminating the concept of CA and ABM. There is a need to follow up the research in looking the application of CA and ABM in developing world context in particular in Southeast Asian countries where major urban population with high growth rate will likely to occur.

### **References**

- Abdou, M., L. Hamill, N. Gilbert. (2012) Designing and building an agent-based model, in: *Agent-based models of geographical systems*, Springer, 141-165.
- ADB. (2011) *Inclusive cities*. Manila: ADB
- Alonso, W. (1960) A theory of the urban land market, *Papers in Regional Science* 6 (1), 149-157.

- Batty, M. and Y. Xie. (1994) From cells to cities, *Environment and Planning B-Planning & Design* 21(7), 31-48.
- Baynes, T. M. (2009) Complexity in Urban Development and Management. *Journal of Industrial Ecology* 13 (2), 214-227.
- Benenson, I. (1999) Modeling population dynamics in the city: from a regional to a multi-agent approach. *Discrete Dynamics in Nature and Society* 3 (2-3), 149-170.
- Bonabeau, E. (2002) Agent-based modeling: Methods and techniques for simulating human systems, *Proceedings of the National Academy of Sciences of the United States of America* 99 (3), 7280-7287.
- Clarke, K. C. and L. J. Gaydos. (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.
- Clarke, K. C., S. Hoppen, and L. Gaydos. (1997) A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. *Environment and Planning B-Planning & Design* 24 (2), 247-261
- Couclelis, H. (1997) From cellular automata to urban models: New principles for model development and implementation. *Environment and Planning B-Planning & Design* 24 (2), 165-174.
- Couclelis, H. (2001) Why I no longer work with Agents, in: *Meeting the challenge of complexity* (D. C. Parker, T. Berger, S. M. Manson, eds.), Irvine, 14-16.
- Crooks, A. (2006) An Introduction to the Repast Software: Recursive Porous Agent Simulation Toolkit.
- Crooks, A. T. and A. J. Heppenstall. (2012) Introduction to Agent-based modelling, in: *Agent-Based models of Geographical systems* (A. J. Heppenstall, L. See, A. T. Crooks, M. Batty, eds.), Springer, 85-108.
- Engelen, G., C. Lavalle, J. I. Barredo, M. van der Meulen, and R. White. (2007) The MOLAND modelling framework for urban and regional land-use dynamics, in: *Modelling Land-Use Change: Progress and Applications* (E. Koomen, J. Stillwell, A. Bakema, H. J. Scholten, eds.). Dordrecht: Springer.
- Epstein, J. M. and R. L. Axtell. (1996) *Growing Artificial Societies: Social Science from the Bottom Up*. Washington, DC: Brookings Institution.
- Filatova, T., D. Parker, and A. van der Veen. (2009) Agent-based urban land markets: Agent's pricing behavior, land prices and urban land use change. *Journal of Artificial Societies and Social Simulation* 12 (1).
- Fisher-Gewirtzman, D. and E. Blumenfeld-Liberthal. (2012) An agent-based model for simulating urban morphology: Sachnin as a case study. *Survey Review* 44 (325), 162-167.
- Fontaine, C. M. and M. D. A. Rounsevell. (2009) An agent-based approach to model future residential pressure on a regional landscape. *Landscape Ecology* 24 (9), 1237-1254.
- Grimm, V., U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, T. Grand, S. K. Heinz, and G. Huse. (2006) A standard protocol for describing individual-based and agent-based models, *Ecological modelling* 198 (1), 115-126.
- Grimm, V., E. Revilla, U. Berger, F. Jeltsch, W. M. Mooij, S. F. Railsback, H. H. Thulke, J. Weiner, T. T. Wiegand and D. L. DeAngelis. (2005) Pattern-oriented modeling of agent-based complex systems: Lessons from ecology, *Science* 310 (5750), 987-991.
- Irwin, E. G. and J. Geoghegan. (2001) Theory, data, methods: developing spatially explicit economic models of land use change. *Agriculture Ecosystems & Environment* 85 (1-3), 7 - 23.
- Jantz, C. A., S. J. Goetz and M. K. Shelley. (2004) Using the SLEUTH urban growth model to simulate the impacts of future policy scenarios on urban land use in the Baltimore-Washington metropolitan area. *Environment and Planning B-Planning & Design* 31(2), 251-271.

- Lau, K. H. and B. H. Kam. (2005) A cellular automata model for urban land-use simulation. *Environment and Planning B-Planning & Design* 32(2), 247-263.
- Liu, Y. (2008) *Modelling urban development with geographical information systems and cellular automata*. Boca Raton, FL: CRC Press.
- Liu, Y. (2012) Modelling sustainable urban growth in a rapidly urbanising region using a fuzzy-constrained cellular automata approach. *International Journal of Geographical Information Science* 26(1), 151-167.
- Loibl, W. and T. Toetzer. (2003) Modeling growth and densification processes in suburban regions - simulation of landscape transition with spatial agents. *Environmental Modelling & Software* 18 (6), 553-563
- Matthews, R. B., N. G. Gilbert, A. Roach, J. G. Polhill, and N. M. Gotts. (2007) Agent-based land-use models: A review of applications, *Landscape Ecology* 22 (10), 1447-1459.
- Moreno, N., A. Menard and D. J. Marceau. (2008) VecGCA: a vector-based geographic cellular automata model allowing geometric transformations of objects. *Environment and Planning B-Planning & Design* 35 (4), 647-665.
- Moreno, N. L. (2008) A vector-based geographical cellular automata model to mitigate scale sensitivity and to allow objects' geometric transformation, Thèse de doctorat, University of Calgary.
- Naimah, S., H. Rosmiyati and E. E. Yasin Abdalla. (2011) Modelling land use changes at the peri-urban areas using Geographic Information Systems and Cellular Automata Model. *Journal of Sustainable Development* 4 (6), 72-84.
- O'Sullivan, D. and P. M. Torrens. (2001) Cellular models of urban systems, in: *Theory and Practical Issues on Cellular Automata*, Springer, 108-116.
- Park, S., S. Jeon, S. Kim and C. Choi. (2011) Prediction and comparison of urban growth by land suitability index mapping using GIS and RS in South Korea. *Landscape and Urban Planning* 99 (2), 104-114.
- Parker, D. C. (2005) Integration of geographic information systems and agent-based models of land use : prospects and challenges, in: *GIS, spatial analysis, and modeling* (D. J. Maguire, M. Batty, M. F. Goodchild, eds.), ESRI, Redlands, California, 403-422.
- Parker, D. C. and T. Filatova. (2008) A conceptual design for a bilateral agent-based land market with heterogeneous economic agents, *Computers Environment and Urban Systems* 32(6), 454-463.
- Parker, D. C., S. M. Manson, M. A. Janssen, M. J. Hoffmann, and P. Deadman. (2003) Multi-agent systems for the simulation of land-use and land-cover change: A review, *Annals of the Association of American Geographers* 93 (2), 314-337.
- Petrov, L. O., C. Lavallo, and M. Kasanko. (2009) Urban land use scenarios for a tourist region in Europe: Applying the MOLAND model to Algarve, Portugal. *Landscape and Urban Planning* 92 (1), 10-23.
- Sante, I., A. M. Garcia, D. Miranda, and R. Crecente. (2010) Cellular automata models for the simulation of real-world urban processes: A review and analysis. *Landscape and Urban Planning* 96 (2), 108-122.
- Seto, K. C., B. Guneralp, and L. R. Hutyra. (2012) Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools, *Proceedings of the National Academy of Sciences of the United States of America* 109 (40), 16083-16088.
- Silva, E. A., and K. C. Clarke. (2005) Complexity, emergence and cellular urban models: Lessons learned from applying sleuth to two Portuguese metropolitan areas. *European Planning Studies* 13 (1), 93-116.
- Stevens, D., S. Dragicevic, and K. Rothley. (2007) iCity: A GIS-CA modelling tool for urban planning and decision making. *Environmental Modelling & Software* 22 (6), 761-773.



- Thapa, R. B. and Y. Murayama. (2012) Scenario based urban growth allocation in Kathmandu Valley, Nepal. *Landscape and Urban Planning* 105 (1-2), 140-148.
- Tobler, W. (1979) Cellular geography, *Philosophy in geography* 9, 379-386.
- Torrens, P. M. and I. Benenson. (2005) Geographic automata systems. *International Journal of Geographical Information Science* 19 (4), 385-412.
- UN-DESA. (2013) *Population facts*. New York: The United Nations.
- UNFPA. (2007) *The State of World Population 2007* (A. Marshall, ed.). New York, USA: UNFPA
- Vancheri, A., Giordano, P., Andrey, D., Albeverio, S. (2008) Urban growth processes joining cellular automata and multiagent systems. Part 2: computer simulations, *Environment and Planning B-Planning & Design* 35 (5), 863-880.
- Verburg, P. H., P. P. Schot, M. J. Dijst and A. Veldkamp. (2004) Land use change modelling: Current practice and research priorities, *GeoJournal* 61 (4), 309-324.
- Wahyudi, A. (2013) Cellular automata for urban growth modeling: a chronological review on factors in transition rules, in: *13th International Conference on Computers in Urban Planning and Urban Management (CUPUM 2013)* Utrecht, the Netherlands.
- White, R. and G. Engelen. (1993) Cellular-automata and fractal urban form - a cellular modeling approach to the evolution of urban land-use patterns. *Environment and Planning A* 25 (8), 1175-1199.
- Wilson, A. G. (2000) *Complex spatial systems: the modelling foundations of urban and regional analysis*. Pearson Education.
- Wolfram, S. (1983) Statistical mechanics of cellular automata. *Reviews of modern physics* 55 (3), 601-644
- Wu, F. and C. J. Webster. (1998) Simulation of land development through the integration of cellular automata and multicriteria evaluation. *Environment and Planning B-Planning & Design* 25 (1), 103-126.
- Xie, Y., M. Batty and K. Zhao. (2007) Simulating Emergent Urban Form Using Agent-Based Modeling: Desakota in the Suzhou-Wuxian Region in China. *Annals of the Association of American Geographers* 97 (3), 477-495.
- Zhang, H., Y. Zeng, L. Bian, and X. Yu. (2010) Modelling urban expansion using a multi agent-based model in the city of Changsha. *Journal of Geographical Sciences* 20 (4), 540-556.