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Modeling urban vertical growth using cellular automata—Guangzhou as a case study

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A B S T R A C T

Urban development is a complex spatio-temporal process that involves both horizontal and vertical growth. Despite growing recognition of the significance of horizontal development, models of urban vertical growth remain limited. This study aims to develop a GIS-based cellular automata model for exploring the vertical complexities of urban growth. Taking into account a series of variables, including accessibility, population density and building density and height, an "IF-THEN" rule base is designed and employed to simulate different height states of building growth. The model is validated through application to a case study of Guangzhou city for the period of 2001–2010. The results of the proposed model are compared with Guangzhou Urban Planning Bureau reference data for newly authorized construction buildings and then tested using an error matrix for 2001–2005 (overall accuracy 81.2% and Kappa coefficient 74.2%) and a fractal dimension for 2006–2010. Several conclusions are made based on the fractal analysis: (1) low-rise buildings tend to "spread outward," while high-rise buildings exhibit a trend of "compact development"; (2) a "hot zone" of vertical growth in Guangzhou demonstrates that the city is now undergoing a "phase transition" from a mono-center to a bi-center; and (3) low-, moderate-, and high-state buildings are being co-developed and are thus beginning to constitute an important feature of the urban and smart growth landscape.

Introduction

Human civilization is currently entering an Urban Century (Kourtit, Nijkamp, & Reid, 2014). Urban areas are experiencing rapid growth mainly as a result of growing populations, rising incomes, and declining commuting costs (Bruechner, 2000; Bruechner & Largey, 2008). In developing countries in particular, cities are sprawling at rapid rates, as the number of metropolitan areas has increased considerably (Schneider & Woodcock, 2008). Such processes have had a number of negative influences on citizens with respect to their health and health-related behaviors (Ewing, Schieber, & Zegeer, 2003; Ewing, Schmid, Killingsworth, Zlot, & Raudenbush, 2003). Consequently, modern city expansion monitoring, analysis and simulation have become areas of major interest (*e.g.*, Lavalle, Demicheli, Turchini, Casals-Carrasco, & Niederhuber, 2001; Torrens, 2006; Torrens & Alberti, 2000). One notable byproduct of urban sprawl is vertical development, which is reflected in the growth of buildings of various functions (*e.g.*, commercial, residential, and industrial). As this phenomenon can transform the morphology and functioning of a city, it represents one of the most important aspects of smart growth and sustainable development. However, research in this field currently focuses more heavily on horizontal development, in relation to two phenomena in particular. The first focus involves the study of urban sprawl processes that occur outside of major urban centers, particularly along the fringes, edges and peripheries of cities, which transform landscapes from agricultural land into either built-up or less dense suburban areas. This field of research is not only concerned with conversion analyses of rural-urban land along the perimeter of the city (Huang, Zhang, & Wu, 2009) but also examines the urban expansion of downtown areas and major satellite cities (Li, Zhang, & Liang, 2010). The

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other major area of focus involves the simulation of land-use changes across entire city regions, which involves the examination of transitions between several interdependent activities. In-depth studies involving land-use change modeling through the use of unbalanced support-vector machines (Huang, Xie, & Tay, 2009) and analyses of land-use change effects on life cycles (Batty, Xie, & Sun, 1999) have been conducted in the field of land-use-change modeling in recent years.

As noted above, these studies are largely based on two-dimensional spatial patterns that do not account for vertical development. However, with a decline in available land and the recent adoption of policies that protect high-quality arable land, the costs of horizontal growth are increasing significantly, necessitating the exploitation of high-level space. Vertical development is defined as vertical building growth in this study. Although vertical development represents an inevitable response to urban development and is therefore a marker of economic vitality, it can also have negative effects. Representing a large proportion of impervious surfaces in urban environments, buildings can heavily influence urban runoff levels (Weng, 2001) and are closely related to non-point pollutant sources (Hurd & Civco, 2004). In addition, building distribution patterns can significantly influence the nature of the urban heat island effect (Yang, Huang, & Homer, 2003) in addition to amplifying road traffic noise (Ko, Chang, & Lee, 2011). Moreover, the vertical growth of urban landscapes can affect urban efficiency levels as well as resident living habits and lifestyles. For example, residents are more likely to suffer from “traffic congestion” resulting from inefficient commercial and residential building distribution and are more likely to be accustomed to a lifestyle characterized by frequent interaction with others and high population densities. There is thus an urgent need to explore spatial patterns and temporal processes of urban vertical development. It is also especially important that the driving forces behind vertical growth be understood in relation to interactions between local actions and global patterns and, based on this knowledge, that ‘what-if’ decision-making be simulated based on varying combinations of driving forces. Although numerous statistical methods have been employed to capture the complexities of horizontal and vertical urban growth, these methods alone cannot accurately and efficiently quantify dynamic processes of urban growth due to complications arising from spatial heterogeneity and the existence of modifiable areal units (Paez & Scott, 2004). However, computer simulation approaches, such as cellular automata (CA), are frequently and successfully applied in the field of urban analysis and modeling (*e.g.*, issues of urban sprawl, socio-spatial dynamics, segregation, and gentrification have been analyzed) (Batty, 2001; Lagarias, 2012; Linard, Tatem, & Gilbert, 2013; Moghadam & Helbich, 2013). The CA model appears to play a crucial role in generating more comprehensive information on urban patterns and development (He, Okada, Zhang, Shi, & Zhang, 2006). In this paper, we present a GIS-based cellular automata model of urban vertical growth. Importantly, CA offers a bottom-up approach to vertical growth modeling through the use of complex and realistic configurations. A general background on the CA model is provided in the following section. The model's performance is then validated based on a case study of a built-up area of Guangzhou (GZ), a rapidly growing city in southern China.

Cellular automata modeling

The CA model is composed of five principal elements: a lattice, a set of allowed states, neighborhoods defined by the lattice, transition rules and a temporal component (Batty, 2001). Combining these elements, the following simple and fundamental equation for CA is obtained:

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

where S^{t+1} and S^t represent the states of the cell under study at times $t+1$ and t, respectively; Ω^t is the configuration adjacent to the cell under study; f represents a set of transition rules, and T denotes the relevant parameters. Depending on modifications of the aforementioned elements, CA model forms and functions can vary from simple, standard and regular to complex, constrained and irregular. For example, by examining different interpretations of the five components and applying relaxation to the resulting characteristics, Liu developed a systematic scheme for classifying CA models (Liu, 2009). Several advanced forms of cellular models have been developed to distinguish generic from particular cities and realistic from optimal cities. Among these, the following initiatives have been extremely successful in developing cellular theories and useful applications of CA models: the ‘Gigalopolis project,’ jointly designed and developed by the University of California, Santa Barbara (UCSB) and the United States Geological Survey (USGS) (Project Gigalopolis), the ‘GeoSOS group’ at Sun Yat-sen University (Project GeoSOS), the ‘METRONAMICA group’ at the Research Institute for Knowledge Systems (RIKS BV) and the ‘DUEM group’ at the Bartlett Centre for Advanced Spatial Analysis (CASA). Applying five growth coefficients (*e.g.*, diffusion, breed, spread, road gravity, and slope) to six input data layers (*e.g.*, land cover, exclusion, urbanization, transportation, and hill-shade), the first research group divides land-use changes into four categories: spontaneous growth, new spreading center growth, edge growth, and road-influenced growth (Clarke & Gaydos, 1998) and has successfully applied this model to several regions (Clarke & Gaydos, 1998; Clarke, Hoppen, & Gaydos, 1997; Dietzel & Clarke, 2004; Silva & Clarke, 2002; Syphard, Clarke, & Franklin, 2005). Drawing from the preliminary work of Yeh and Li at the University of Hong Kong, the second research group has developed a computer-based system that is designed based on an Object-Oriented Programming (OOP) paradigm. This system notably situates the cellular model with theories from other fields and thus forms an integrated organism. The approach applies methods such as logistic-based CA, multi-criteria evaluation (MCE)-based CA (Wu & Webster, 1998), principal components analysis (PCA)-based CA (Li & Yeh, 2001b, 2002b), artificial neural network (ANN)-based CA (Li, Lao, Liu, & Chen, 2011; Li & Yeh, 2001a, 2002a) and ant colony optimization (ACO)-based CA (Liu & Li 2008; Li et al., 2011; Liu, Li, & Yeh, 2007). The latter two research groups have also produced significant findings in this field (*e.g.*RIKS BV, 2005; Van Delden, Escudero, Uljee, & Engelen, 2005; Xie, 2002). Due to the recent development of CA theories and their successful application in various studies, CA is employed in this study to simulate urban vertical development for examining building growth height states.

However, the model-building process is complicated by the presence of various building representations. For example, the basal areas for buildings with different functions range from 10^2 m^2 (for residential buildings) to 10^5 m^2 (for warehouse buildings). Thus, it is in practice either difficult or even impossible to associate cells with buildings. In addition, as several distinct activities may occur within one building, it is inaccurate to refer to buildings as cells. In consideration of these particularities, we have developed a GIS-based CA model that uses a linguistic approach. This model focuses on the simulation of an actual city (*i.e.*, Guangzhou, particularly in terms of vertical growth) from 2001 to 2010. By combining a series of spatial variables, the model is designed to capture building distribution patterns across space and time.