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A game-theory based agent-cellular model for use in urban growth simulation: A case study of the rapidly urbanizing Wuhan area of central China

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ABSTRACT

Accurate modeling of urban growth is an extremely important component of urban geographic studies and is also vital for future urban planning. The trajectories of urban growth can be monitored and modeled by the use of geographic information system techniques, remote sensing data, and statistical analysis. In this study, we couple game theory with an integrated agent-cellular method to develop a model of the major determinants controlling urban development, which not only accounts for socioeconomic driving forces but also captures human actions. Wuhan, the largest city in central China, is undergoing rapid urbanization and is facing uncontrolled urban expansion. The city proper region of Wuhan is selected as the case study area to simulate urban growth during the period between 2003 and 2023. The results indicate that the social conflicts between the different stakeholders in urban development can be identified by utilizing a game tree. The game-theory based agent-cellular model is shown to be more effective than a pure cellular automata model in urban growth simulation. The results also show that, from 2013 to 2023, the urban area of the Wuhan city proper region is predicted to grow to 442.77 km^2, which is almost two times the area in 2003. This research is the first study to use empirical data and game theory to analyze the decision-making process in urban development in the Wuhan area.

1. Introduction

Urbanization is a topic that is of great concern to urban researchers (Antrop, 2004; Su, Xiao, Jiang, & Zhang, 2012; Sun, Wu, Lv, Yao, & Wei, 2013). The process, which is characterized by large rural population migration into cities, coupled with an unprecedented scale and rate of urban expansion, is one of the crucial issues of environmental change in the 21st century in most urbanized countries and regions, especially in the developing world (Deng, Wang, Hong, & Qi, 2009; Seto & Fragkias, 2005; Sui & Zeng, 2001; Tian, Jiang, Yang, & Zhang, 2011; Wu & Zhang, 2012). Since the initialization of economic reforms in 1978, China has witnessed unprecedented economic growth and, notably, urbanization. In this context, a massive amount of open and agricultural land in Chinese cities has been converted to developed use in the last two decades (Su, Jiang, Zhang, & Zhang, 2011). According to the United Nations (2012), the projected urban population of China will reach more than one billion by 2050. Therefore, the amount of land resources used in urban development will continue to increase, and the lack of agricultural land protection will become more and more of an issue. Accurate projection of future urban growth distribution is very important for evaluating the ecological and environmental impacts, characterizing the spatial pattern of landscape changes, and providing fundamental tools for land-use planning and regional sustainability strategies.

For this study, we select Wuhan, which is the capital of Hubei Province and the largest city of central China. Because a great deal of research has concentrated on the urban growth of the Yangtze River Delta and the Pearl River Delta, empirical case studies are still very few in central China. In particular, Wuhan, the largest political and economic center in central China, has not been systematically studied in the existing literature on urban growth patterns. Although the market-oriented reforms initiated in the late 1970s and early 1980s brought about rapid socioeconomic changes in China, the development of Wuhan has lagged behind for political reasons, the economic strategy in the 1980s and 1990s, and its

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disadvantageous location far from coastal areas (Qiao et al., 1999). Consequently, the urban growth rate in Wuhan was relatively low during this period. Since the strategy of "promoting the central region" was launched in 2009, Wuhan has exhibited rapid economic growth, due to the support of government, and has received investment from all over the world. To make the simulation in this study more reasonable and more similar to the operation of human and natural systems in the real world, we present a game-theory based agent-cellular model and take Wuhan as a case study to fulfill this task.

2. Literature review

Urban growth is an evolutionary spatial and social process that relates to the changes of urban area and the transformation of people's lifestyle at different scales (Han, Hayashi, Cao, & Imura, 2009). To model historical urban morphology and to forecast future scenarios, scholars have developed a large number of approaches to simulate urban land-use changes. These models can generally be classified into two categories: top-down and bottom-up models. The top-down models, which are mainly based on traditional macroeconomic theories and are largely derived from gravity-based models, cannot deal with micro-level planning (Lee Jr., 1973) or social and environmental problems (Itami, 1994). With the ongoing development of the computer algorithms used in urban geography, the bottom-up models have gradually replaced the top-down models in the field of urban dynamics modeling.

Among the bottom-up models, cellular automata (CA) models have been widely used in urban dynamics simulation (Barredo, Kasanko, McCormick, & Lavalle, 2003; Batty, Xie, & Sun, 1999; Feng, Liu, Tong, Liu, & Deng, 2011; Han et al., 2009; Li & Yeh, 2000; Luo & Wei, 2009; Santé, García, Miranda, & Crecente, 2010; White, Engelen, & Uljee, 1997; Wu, 2002). With the help of geographic information systems (GIS) and remotely sensed data, CA models can capture the rough urban morphology in the future through simple and flexible transition rules (Santé et al., 2010; Torrens, 2000). The main characteristic of CA to project the spatial form of urban area is that it abstracts the physical real world, using discrete lattice grids, and presents complex global behavior from simple local rules, representing cell changes in response to neighboring effects over a time span (Fang, Gertner, Sun, & Anderson, 2005; Haase, Haase, Kabisch, Kabisch, & Rink, 2012; Santé et al., 2010). Many CA and CA-based models have been employed to study the complex environment of urban development and have successfully demonstrated the capability of modeling urban landscape evolution (Feng et al., 2011; García, Santé, Boullón, & Crecente, 2012; Han et al., 2009; He, Zhao, Tian, & Shi, 2013; Jantz, Goetz, Donato, & Claggett, 2010; Sathish Kumar, Arya, & Vojinovic, 2013; Vliet, White, & Dragicevic, 2009). However, traditional "bottom-up" CA models cannot capture the macro social and economic driving factors of urban growth (Han et al., 2009; White & Engelen, 2000), and have done little to link CA with urban theory (Torrens & O'Sullivan, 2001). In particular, CA models do not incorporate human decision-making to produce an accurate simulation (Haase, Lautenbach, & Seppelt, 2010; Jokar Arsanjani, Helbich, & de Noronha Vaz, 2013). Finally, the CA cells cannot move in space, so the CA models often neglect the links between cells and the overall patterns at a greater spatial scale (Benenson, Omer, & Hatna, 2002; Qi et al., 2004).

Another important approach currently receiving much attention in the land-use modeling community is the agent-based modeling approach (ABM) (Jjumba & Dragićević, 2012; Matthews, Gilbert, Roach, Polhill, & Gotts, 2007; Parker, Manson, Janssen, Hoffmann, & Deadman, 2003; Robinson, Murray-Rust, Rieser, Milicic, & Rounsevell, 2012; Waddell, 2002). These models analyze the dominant players of land-use change in the real world and simulate their behaviors, as well as concentrate on their interactions among these "agents" (Table 1). ABM consists of a number of "agents" that can model the interaction between humans and their environment, and can make choices and decisions in response to this interaction (Matthews et al., 2007). The aggregated individual behaviors of these agents determines the behavior of the whole system. The advantages of ABM are exactly what CA models lack, which include the following: (1) agents can have different properties and actions, which can represent human behavior in the real world (Jokar Arsanjani et al., 2013; Matthews et al., 2007); (2) agents can change their behaviors or make decisions based on their links with both each other and the environment (An, 2012; Crooks, 2006; Parker et al., 2003; Verburg, 2006); and (3) agents can be constructed at different scales; i.e., they can be organizations as well as individuals (Verburg, 2006). These advantages allow ABM techniques to incorporate human decision-making into a social process simulation in a mechanistic and spatially explicit way (Matthews et al., 2007; Robinson et al., 2012; Wu, Mohamed, & Wang, 2011). In terms of urban growth simulation, agents can represent the different types of decision-makers that lead to the conversion from non-urban to urban land, such as residents, peasants, government, and developers (Li & Liu, 2007; Zhang, Zeng, Bian, & Yu, 2010). The result of the "game" between these agents determines the urban land-use transition. However, it is currently difficult to define the agents' properties and to use empirical data to translate the complex behavior of human beings into rules in the practical application of ABM (Li & Liu, 2007).

Although such modeling approaches have allowed huge progress in urban development studies, some scholars believe that, in general, no single modeling approach can satisfactorily answer the question of how the socio-spatial dynamics of land-use develop in a complex urban system, and a specific combined approach, benefiting from synergy and complementarity, will result in more satisfying simulation results (Haase et al., 2012). In addition, in urban geography, both CA and ABM have been widely employed to simulate future urban growth. Therefore, a great number of scholars have tried to utilize integrated agent-cellular models to model the spatial pattern of urban development and other fields of social science, in which the CA accounts for the environmental infrastructure, while the ABM represents the different kinds of agents. For example, Robinson et al. (2012) integrated CA-like rules into three broad types of ABM models to capture the actions of different organizations and thus to model the urban growth in Koper, Slovenia. They also evaluated the impact of land use on the agricultural systems and people's life. The model results showed that the urban growth had disproportionately influences on the high-quality agricultural soils. Meanwhile, the people's life can be improved by the clustering of industrial development. Li and Liu (2007) also presented an integrated cellular-agent model to represent the residential development of Guangzhou city in China. In their model, three categories of agents, namely resident, developer, and government, were developed, while a logistic CA model was employed to represent the physical factors through incorporating of a set of spatial determinants. This study demonstrated that an integrated model was better than a single CA model in simulating the growth of urban land used for residential uses in their study area. Similarly, Wu et al. (2011) constructed an integrated model using three spatial scales (agents, cells, and provinces) to model the China's population growth and its spatial distribution since 2 A.D. In this study, ABM was used to represent individual members that can move in a cell and CA was employed to represent the geographic conditions. The cell was considered the fundamental unit, and a cluster of cells within the same region was regard to be a province which have all the macro information of the cells within them. The agents then use