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Assessing cellular automata model behaviour using a sensitivity analysis approach

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Abstract

Rapid advances in computer and geospatial technology have made it increasingly possible to design and develop urban models to efficiently simulate spatial growth patterns. An approach commonly used in geography and urban growth modelling is based on cellular automata theory and the GIS framework. However, the behaviour of cellular automaton (CA) models is affected by uncertainties arising from the interaction between model elements, structures, and the quality of data sources used as model input. The uncertainty of CA models has not been sufficiently addressed in the research literature. The objective of this study is to analyze the behaviour of a GIS-based CA urban growth model using sensitivity analysis (SA). The proposed SA approach has both qualitative and quantitative components. These components were operationalized using the cross-tabulation map, KAPPA index with coincidence matrices, and spatial metrics. The research focus was on the impacts of CA neighbourhood size and type on the model outcomes. A total of 432 simulations were generated and the results suggest that CA neighbourhood size and type configurations have a significant influence on the CA model output. This study provides insights about the limitations of CA model behaviour and contributes to enhancing existing spatial urban growth modelling procedures.

Keywords: Sensitivity analysis; Cellular automata; Spatial metrics; Geographical information system (GIS); Spatial modelling; Land-use change

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1. Introduction

The expansion of urban areas into existing forested and agricultural lands is a local and global planning issue of great concern. As urban areas expand, the need for housing and other amenities intensify. Municipalities endeavour to keep up with these demands by balancing multiple development and conservation goals, and depend heavily on the descriptive and predictive capabilities of urban models. Improving the reliability of urban growth models is therefore a crucial requirement to aid sustainable growth policies and planning.

Complex systems theory has been widely used to model cities and their evolution. Cities are characterized by a large number of interacting components and have several key signatures such as fractal dimensionality, self-similarity, self-organization and emergence making them suitable to be modelled as complex systems (Allen, 1997; Batty & Longley, 1994; Portugali, 2000; Torrens & O'Sullivan, 2000). The evolution of cities, or urban growth, is a complex spatial process and hence a general perspective can be adopted for its analysis to derive a framework for effective planning and decision making. For more than a decade, research focus has been on using *cellular automata theory* to create spatial modelling approaches for analyzing the spatial complexity and self-organizing properties of urban growth processes. The concept of cellular automata was initially proposed by John Von Neumann during the 1950s (Batty, 1997). The subsequent "Game of Life" application developed by John Conway during the 1970s contributed to the popularity of cellular automaton (CA) design. The Game of Life application consisted of a typical grid of cells (alive or dead) where the possibility of the cell state was determined by simple transition rules (Batty & Xie, 1994).

Cellular automata has been linked to the work of spatial diffusion (Hägerstrand, 1967) and segregation (Schelling, 1971) modelling approaches, but Waldo Tobler (1979) was the first to defined CA as geographical model. Later, Couclelis (1985) used discrete systems theory to propose an alternative formulation of the cellular spaces. White and Engelen (1993, 1997) modelled urban growth with a constrained CA model in which cell states represented land-uses, and the transition rules expressed the potential of a change from one state to another as a function of existing land-use. Clarke and Gaydos (1998) proposed the SLEUTH model to simulate the historical urban growth for San Francisco and the Washington/Baltimore region. Li and Yeh (2000) applied a CA model based on land suitability by incorporating local, regional and global constraints that affect the modelling dynamics. In recent times, there has been a renewed interest in advancing CA to improve its capacity to model and simulate urban growth (Batty, 1998; O'Sullivan & Torrens, 2000). Wu and Webster (1998) applied multi-criteria evaluation into CA simulation to account for non-deterministic transition rules. Torrens (2001) integrated CA and multi-agent approaches to support the exploration of what-if scenarios for urban planning and management. Further, a neural network structure was suggested to overcome the limitations of defining parameter values (Yeh & Li, 2003).

A reason for the increasing attention given to CA models is the ease with which they can now be integrated and programmed in raster-based geographic information system (GIS) environments. In addition, the ability to change spatial resolutions in the GIS makes the integration useful for exploring a variety of bottom-up modelling strategies. For urban growth studies, this bottom-up approach is useful since simple local rules can be used to evolve complex global patterns (Wolfram, 1984). Specifically, one can represent the spatial complexity and dynamics of urban growth by selecting various configurations of the basic