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A land-use spatial optimization model based on genetic optimization and game theory

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ABSTRACT

Land-use patterns can be considered as a consequence of competitions between different land-use types. How to coordinate the competitions is the key to land-use spatial optimization. In order to improve the ability of existing land-use spatial optimization models for addressing local land-use competitions (the competitions on land units), a loosely coupled model based on a genetic algorithm (GA) and game theory is constructed. The GA is repeatedly executed to separately optimize the spatial layout of each land-use type. The land-use status quo is overlaid with the optimization results to find local land-use competitions. The concept of land-use competition zones is introduced in this study. Using the competition zones as the basic units, the model utilizes multi-stakeholder games and the knowledge of land-use planning to coordinate the local land-use competitions. The final solution is obtained after the land-use coordination. Gaoqiao Town, Zhejiang Province is selected as the study area to verify the validity of the model. The experimental results confirm that the model is feasible to undertake land-use spatial optimization and to coordinate the competitions between different land-use types.

1. Introduction

Land-use spatial optimization is a complicated spatial decision-making problem with multiple conflicting objectives. How to coordinate land-use competitions is the key to land-use spatial optimization. The quantitative constraints of land resources and their multi-suitability are the main reasons for these competitions (Chen, 2007; Liu, Wang, & Long, 2008). From the spatial perspective, land-use competitions can be considered as a scramble for land units between multiple land-use types; however, in essence these competitions are a conflict of interest between multiple stakeholders (Zhang, Li, & Fung, 2012).

Many researchers have performed extensive research in the field of land-use optimization. The existing optimization models can be roughly divided into the following three categories: linear programming models, cellular automata models, and models based on intelligent algorithms. Linear programming models can quickly determine the optimal land-use structure according to specific objectives and constraints (Arthur & Nalle, 1997; Chuvieco, 1993; Sadeghi, Jalili, & Nikkami, 2009); however, these models are unable to change the land use of parcels and to undertake spatial optimization (Santé-Riveira, Crecente-Maseda, & Miranda-Barrós, 2008). Cellular automata models are based on land-use conversion rules for local areas and can generate different land-use patterns under different conditions using a bottom-up approach (Li & Yeh, 2000, 2002). Irrational land use in local areas can be adjusted using well-designed land-use conversion rules. However, optimization objectives and other important macroeconomic factors cannot be easily incorporated into cellular automata models.

Land-use spatial optimization is a complicated combinational optimization problem. The computational intensity increases exponentially as the scale of the problem increases when using an exhaustive search to solve the problem (Xiao, 2008). For many real-world applications, numerous spatial variables are involved, and many spatial and non-spatial constraints need to be handled. Conventional mathematical models are not able to find the optimal solution within an acceptable timeframe (Aerts, Eisinger, Heuvelink, & Stewart, 2003). Therefore, as a compromise between the timeframe and the optimality of the final solutions, various intelligent algorithms for land-use spatial optimization have been developed, such as simulated annealing algorithms (Aerts & Heuvelink, 2002; Santé-Riveira, Boullón-Magán, Crecente-Maseda, & Miranda-Barrós, 2008), particle swarm algorithms (Liu, Li, Shi, Huang, & Liu, 2012; Liu, Liu, Liu, He, Jiao, et al., 2012; Liu, Wang, Ji, Liu, & Zhao, 2012), ant colony algorithms (Li, Shi, He, & Liu, 2011; Liu, Li, et al., 2012), and genetic algorithms (GAs). While these algorithms may not be able to obtain the optimal solution for every case, near-opti-

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mal solutions are often good enough to support decision-making for regional land-use planning. Geographic information systems (GISs) play an important role in the application of the intelligent algorithms to land-use spatial optimization (Wu & Grubesic, 2010). These algorithms and GIS can be loosely coupled through the exchange of data files. GIS are utilized to process and visualize spatial data for these algorithms. Moreover, for open GIS, part of GIS functions can be reused in the development of these intelligent algorithms.

GAs are widely used among the aforementioned intelligent algorithms (Goldberg, 1989; Zhou & Sun, 1999). This technique has been applied to solve common spatial optimization problems, e.g., facility location (Brookes, 1997, 2001; Li & Yeh, 2005), forestry planning (Ducheyne, De Wulf, & De Baets, 2006; Fotakis, Sidiropoulos, Myronidis, & Ioannou, 2012), water resource allocation (Fotakis & Sidiropoulos, 2011), and land-use optimization (Holzkämper & Seppelt, 2007; Lautenbach, Volk, Strauch, Whittaker, & Seppelt, 2013; Porta et al., 2012; Stewart, Janssen, & van Herwijnen, 2004). Pareto front based methods are often integrated with GAs to illustrate the trade-off among conflicting optimization objectives, which assists planners in addressing regional-scale land-use competition (Balling, Taber, Brown, & Day, 1999; Bennett, Xiao, & Armstrong, 2004; Cao et al., 2011; Morio, Schädler, & Finkel, 2013). However, these GA-based optimization models do not consider local land-use competitions (the competitions on land units). The genetic operators have been improved from the random search techniques to being combined with the knowledge of land-use planning in previous studies (Cao, Huang, Wang, & Lin, 2012); however, the combination is simple. These operators lack an effective game-based coordination mechanism for local land-use competitions. The important role of interest factors is ignored in the coordination, which may lead to difficulty in implementing the coordination results.

Game theory can simulate the decision behavior of various stakeholders in a conflict of interest and assist them in making the most favorable decision (Rasmusen, 2001; Zhang, 2004). Relevant studies have applied game theory to monitor land-use changes (Wu, Wu, & Shen, 2005), allocate water resources (Liu, Sun, Gu, & He, 2002), cope with multi-objective optimization (Lee, 2012), and solve land-use conflicts (Hui & Bao, 2013). However, game theory methods are usually applied in isolation and have been rarely coupled with land-use optimization models. In consideration of the difficulty in coupling the genetic operators with game theory methods, a loosely coupled model based on a genetic algorithm and game theory is constructed in this study. The model is intended to improve the ability of existing land-use spatial optimization models for addressing local land-use competitions. The second part of this study provides the details of the model. The third part introduces the study area and relevant data. The corresponding experimental results are described and analyzed in the fourth part, and the relevant conclusions are given in the final part.

2. The land-use spatial optimization model

The land-use spatial optimization model in this study consists of two parts (Fig. 1). In the first part, an improved GA is repeatedly executed to separately optimize the spatial layout of each land-use type. In the second part, the land-use status quo is overlaid with the optimization results from the first part to find local land-use competitions. The concept of land-use competition zones is introduced in this study (see Section 2.2). Using the competition zones

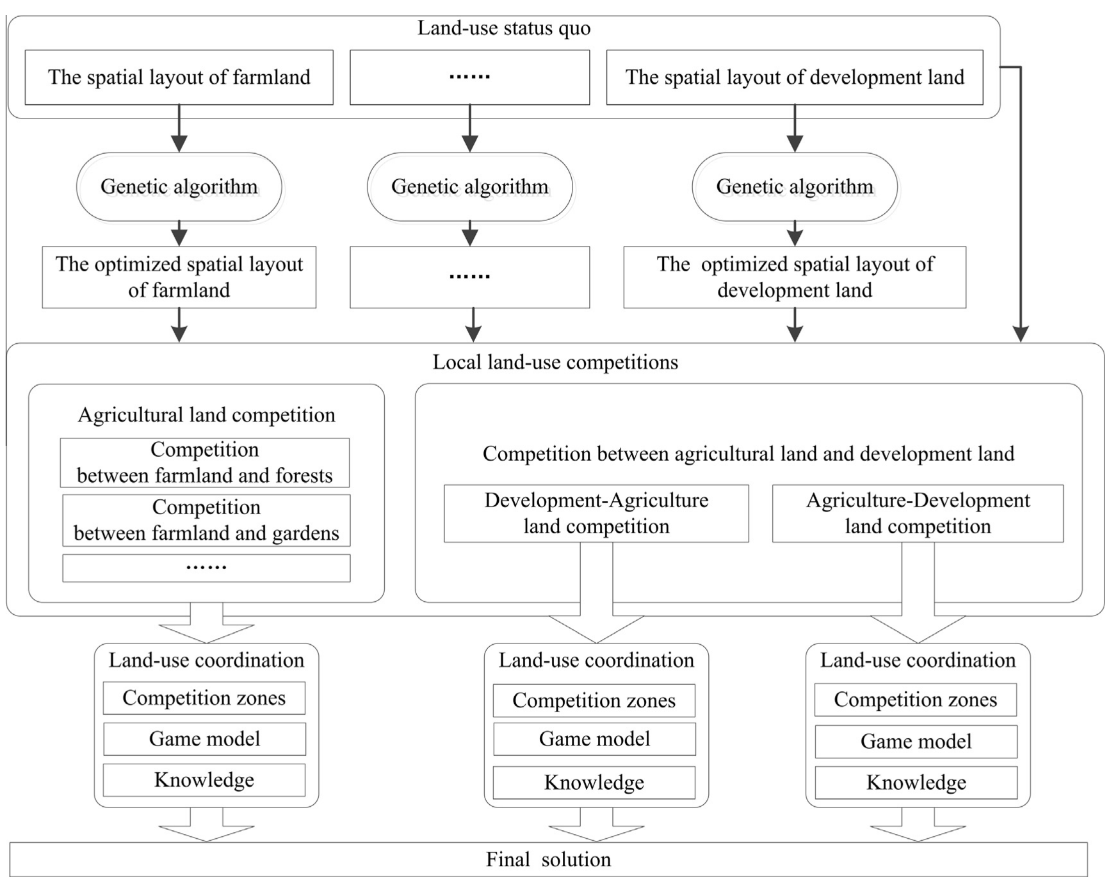

Fig. 1. Model framework.