A Spatial Optimization Approach for Vector-based Land Use Planning

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Abstract

Sustainable land use planning is essential for addressing the dilemma between economic growth and environment protection. Sustainable land use patterns are inherently spatial, which can be structured and addressed using spatial optimization that integrates geographic information systems (GIS) and mathematical models. Most existing work, however, relies on raster data due to its simple data structure and ease of spatial relationship evaluation, which fails to reflect the land use planning practice in reality. This research proposes a spatial optimization approach to seek sustainable land use plans using vector data. Specifically, an evolutionary algorithm is developed to find the set of efficient (Pareto) solutions given the complexity of vector-based representations of space. The empirical study demonstrates the effectiveness of the proposed approach and the superiority to the raster-based land use optimization.

Keywords: Spatial optimization; Genetic algorithm; Land use planning; Vector data

1 Introduction

Sustainable land use planning has significant implications for the quality of life and the living environment, which is intended to arrange various land uses over geographic space to meet the demand of diverse land-use activities, often constrained by economic, social and environmental conditions. Land-use planning problems are therefore spatial in nature and can be structured and addressed using spatial optimization integrating GIS and mathematical models (Church, 2002; Murray, 2010). Most approaches and applications, however, have relied upon raster data which have simple data structure for assessing spatial relationships. This research is to develop an evolutionary algorithm for generalized land-use optimization models using vector data that better reflects the actual shape and spatial layout of parcels, seeking efficient solutions for multi-objective problems.

2 A Spatial Optimization Approach

2.1 Model

Consider the following notation:

i = index of land parcels;

k = index of land use types;

U_k, L_k = upper and lower bounds on total area for land use type k;

a_i = area of parcel i;

k_i = current land-use type of parcel i;

$c_{kk'}$ = cost/km^2 for conversion between land-use types k' and k;

Ω_i = {j; j is a neighbor of i in space, that is, i and j are adjacent};

x_{ik} = 1 if parcel i is assigned land-use type k, 0 otherwise;

A spatial optimization model for land use planning involving two objectives can be formulated as follows:

$$\textit{Maximize} \quad \sum_k \sum_i \sum_{j \in \Omega_i} x_{ik} x_{jk} \qquad (1)$$

$$\textit{Minimize} \quad \sum_i \sum_k c_{k_i k} a_i x_{ik} \qquad (2)$$

$$\textit{Subject to} \quad \sum_k x_{ik} = 1 \quad \forall i \qquad (3)$$

$$\sum_i \sum_k a_i x_{ik} \le U_k \quad \forall k \qquad (4a)$$

$$\sum_i \sum_k a_i x_{ik} \ge L_k \quad \forall k \qquad (4b)$$

$$x_{ik} \in \{0,1\} \quad \forall i,k \qquad (5)$$

Objective (1) is to maximize the compactness by encouraging the same land use to be assigned to adjacent parcels, which does not guarantee but implicitly promotes the contiguity of the regions with the same land use (Aerts et al., 2003). Objective (2) attempts to minimize the total costs. Constraints (3) require only one type of land use allocated to each parcel. Constraints (4a) and (4b) set the range of the desired acreage for each land use. Constraints (5) indicate that the values of the decision variables are binary (0 or 1).

2.2 Solution Procedure

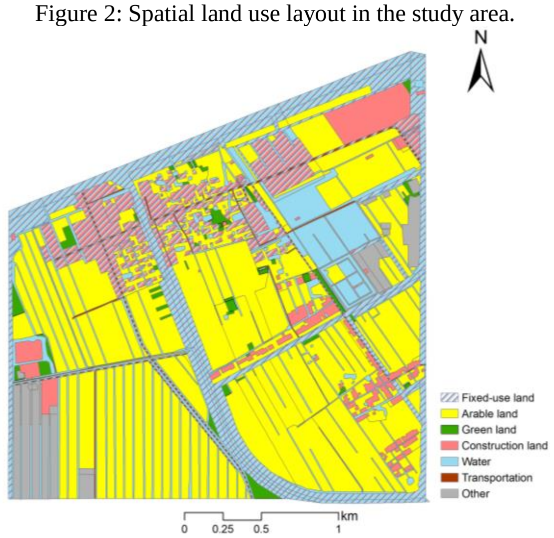
The proposed solution procedure for the model, (1) - (5), is presented in Figure 1, and is built upon the non-dominated sorting genetic algorithm II (NSGA-II) of Deb et al. (2002). One challenge in using vector data for spatial land-use optimization is to meet the allowance constraints for each land use. It is straightforward for raster data that consists of same-size grid, making the area calculation equivalent to counting the number of total cells of same land use. Further, for raster data, Steps 5 and 6 might bring no area changes to each land use if the number of parcels of each type remains the same even though their spatial layout might be altered. However, for vector representation, Steps 5 and 6 might lead to very different area allocation for each land use due to the diverse size of parcels. Thus, it is more complex to assess and meet the land-use quantity constraints if using vector data, and the feasibility amendment in Step 7 is crucial.

Figure 1: An evolutionary algorithm for land-use optimization.

3 Empirical Results

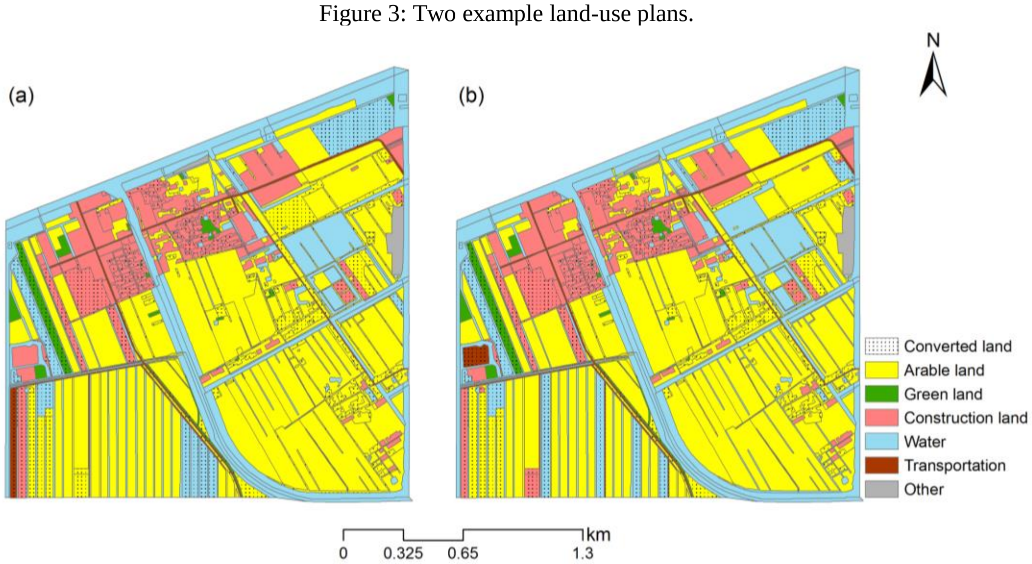
The study area is in the urban fringe located in Dafeng, Jiangsu Province, China, covering part of Chuandong Farm and Caodianmiao Town (Figure 2). The region consists of 680 parcels with a total area 6.52 km^2, which are grouped into six land-use categories according to national regulations: arable land, green land, construction land, water, transportation and other (undeveloped) land. The primary planning goal is to increase urban construction and transportation land by 3-12% and 4-6%, respectively, mainly through transforming undeveloped land which can be reduced by 50-90%. The area of all the other land uses can vary by ±10%.

Figure 2: Spatial land use layout in the study area.



Using a crossover probability 0.6 and a mutation probability 0.03 as an example, Figure 3 shows two land-use plans from the set of Pareto solutions and the parcels involved in the conversion: one with the highest compactness and cost (Figure 3(a)) and the other with the worst compactness but the lowest cost (Figure 3(b)). As can be seen, the compactness of arable, green and construction land in Figure 2 are improved compared to the original land-use layout in Figure 1. However, compared to Figure 3(b), the newly added arable land (on the bottom right) and water facilities (on the central bottom) makes the plan in Figure 3(a) has better compactness. Further, the increase in construction and transportation land are mainly achieved by transforming arable and undeveloped

Figure 3: Two example land-use plans.



land. For example, the construction land is expanded mainly through transforming the surrounding arable land. There are also conversions between other types of land uses, such as arable land and water, and arable and green land.

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