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An interval fuzzy chance-constrained programming model for sustainable urban land-use planning and land use policy analysis

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ABSTRACT

In this study, an interval fuzzy chance-constrained land-use allocation (IFCC-LUA) model is developed for sustainable urban land-use planning management and land use policy analysis under uncertainty. This method is based on an integration of interval parameter programming (IPP), fuzzy flexible linear programming (FFLP) and chance-constrained programming (CCP) techniques. Complexities in land-use planning management system can be systematically reflected, thus applicability of the modeling process can be highly enhanced. The developed method is applied to planning land-use allocation practice in Nanjing city, China. The objective of the IFCC-LUA is maximizing net benefit from LUA system and the main constraints include investment constraints, land suitability constraints, water/power consumption constraints and wastewater/solid waste capacity constraints. Modeling results indicate that desired system benefit will be between [1.34, 1.74] × 10^{12} yuan under the minimum violating probabilities; the optimized areas of commercial land, industrial land, agricultural land, transportation land, residential land, water land, green land, landfill land and unused land will be [290, 393] hm^2, [176, 238] hm^2, [3245, 4390] hm^2, [126, 170] hm^2, [49, 66] hm^2, [1241, 1679] hm^2, [102, 138] hm^2, [7, 10] hm^2 and [178, 241] hm^2. They can be used for generating decision alternatives and thus help decision makers identify desired land use policies under various system-reliability constraints of economic development requirement and environmental capacity of pollutant. Tradeoffs between system benefits and constraint violation risks can also be tackled.

Introduction

Land-use planning may be defined as the process of allocating different activities or uses (such as agriculture, manufacturing industries, recreational activities or conservation) to specific units of area within a region (Stewart et al., 2004; Haque and Asami, 2014), and it is a priority for city communities throughout the world (Wernstedt and Hersh, 1998). As one of the core research aspect in land use planning, the optimal allocation of land use is soon becoming the key measure for sustainable land utilization (Verburg et al., 2013). It is generally impossible for an allocation to achieve a maximum benefit with respect to each land-use goal simultaneously (Bagdanavičiūtė and Valiūnas, 2013). Thus land-use allocation (LUA) is an area where techniques of optimization model can be profitably applied (Chakir and Le Gallo, 2013).

LUA problems involve selecting tracts of land for residential developments, recreational facilities, industrial parks, landfills or many other uses (Cao and Ye, 2013; Li et al., 2014). Models, methods, and researches in several disciplines have been developed for LUA and can support land use policy analysis (Liu et al., 2013). Research results on LUA techniques are the subject of an abundant literature. For example, Gilbert et al. (1985) presented a multi-objective integer programming model for allocating an area of land for development. Mendoza (1987) proposed a linear programming model for LUA of agroforestry systems. Antoine et al. (1997) used a multi-criteria decision analysis (MCDA) technique which was based on the Aspiration-Reservation Based Decision Support (ARBDS) approach to support LUA, considering simultaneously several objectives. Cromley and Hanink (1999) presented a LUA model which coupled linear programming (LP) method and raster geographic information system (GIS). Ligtenberg et al. (2001) proposed a LUA model which combines a multi-agent simulation (MAS) approach with cellular automata (CA). McDonald (2001) designed

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a standard microeconomic model for cost–benefit analysis of LUA. Irwin and Bockstael (2002) developed a spatially distributed agent model for LUA in considering with local spillover effects. Aerts et al. (2003) used a linear integer programming (LIP) method to optimize multi-site LUA. Svoray et al. (2005) developed a habitat heterogeneity model (HHM) incorporated in GIS to support urban LUA. Santé and Crecente (2007) proposed a decision support system for rural LUA using GIS and a multi-objective programming method, while Santé-Riveira et al. (2008a,b) used a GIS-based method to support rural LUA through three sub-models: land suitability evaluation model, land-use area optimization model, and spatial allocation model. Santé-Riveira et al. (2008a,b) developed a simulated annealing-based model for multi-objective LUA. Sharawi (2006) applied the Little–Mirrlees–Squire–van der Tak (LMST) approach for the cost–benefit analysis of LUA. Ligmann-Zielinska et al. (2008) presented a new spatial multi-objective optimization model for sustainable LUA, which encourages efficient utilization of urban space through infill development, compatibility of adjacent land uses, and defensible redevelopment. Puertas et al. (2014) proposed a hybrid LUA model which coupled a logistic regression model, Markov chain, and cellular automata. Stewart and Janssen (2014) proposed a GIS-based multi-objective LUA algorithm.

The above LUA models can be classified to four types: mathematic quantitative optimization model, spatial optimization model, agent-based model and economic model. These models can effectively handle the LUA problems in the urban and rural areas. However, they have two main shortcomings:

First, they cannot reflect the uncertainties in the land-use system (Dalla-Nora et al., 2014). In real world, there are many uncertainties existing in land-use system. For example, the benefit or cost from land-use system may be high, medium or low. An effective method to describe this type of uncertainty is fuzzy sets theory, which can use membership function to model the uncertainty. In addition, the quality or suitability of land may also be expressed as membership function. Moreover, the land investment from the government could be stochastic and can be modeled by probability distribution function; the wastes from the land-use system may be uncertain as a result of various land-use practices, and the discharge of wastes may float between two values. This type of uncertainty can be effectively handled by using an interval parameter programming model. A broad spectrum of previous system optimization methods that deal with these three types of uncertainties in other application areas (such as municipal solid waste management, water quality management, petroleum waste allocation, energy management, flood diversion planning, and so on) are available (Liu et al., 2000; Yeomans, 2007; He et al., 2008; Lin et al., 2009; Verburg and Overmars, 2009; Guo et al., 2010; Li et al., 2010; Xu and Qin, 2010; Zhang et al., 2010; Li and Chen, 2011; Xie et al., 2011; Chen et al., 2012; Lu et al., 2014; Zhou et al., 2014). They include interval parameter programming (IPP), fuzzy flexible linear programming (FFLP), chance constrained programming (CCP) and their integration. For example, Yeomans (2007) applied an interval parameter programming method to solid waste planning. He et al. (2008) developed a simulation-based fuzzy chance-constrained programming method for optimal groundwater remediation under uncertainty. Lin et al. (2009) proposed an interval fuzzy two-stage stochastic optimization model for regional energy systems planning under uncertainty. Guo et al. (2010) proposed an inexact fuzzy-chance-constrained two-stage mixed-integer linear programming approach for flood diversion planning under multiple uncertainties. Li et al. (2010) proposed an inexact fuzzy-stochastic programming approach for energy and environmental systems planning. Xu and Qin (2010) developed an inexact double-sided fuzzy chance-constrained model for agricultural effluent control under uncertainty. Zhang et al. (2010) proposed a fuzzy-robust stochastic multi-objective programming approach for petroleum waste management planning. Li and Chen (2011) used a fuzzy-stochastic-interval linear programming method to support municipal waste management. Xie et al. (2011) used an inexact chance-constrained programming method to support water quality management. Chen et al. (2012) developed an interval parameter programming method for planning regional electric power systems and managing carbon dioxide. Lu et al. (2014) developed a multi-objective interval stochastic LUA model for Suzhou, China. Zhou et al. (2014) proposed an interval fuzzy national-scale land-use model (IFNLM) for China. However, there were few studies on land-use planning management under multiple uncertainties in most previous studies.

Another disadvantage of previous LUA models is: many important environmental and ecological factors are not comprehensively considered and economic benefits/political factors are always the main concern (de Freitas et al., 2013; Karrasch et al., 2014; Kanianska et al., 2014). The environmental and ecological impacts are not systematically examined and corresponding violating analysis is not properly conducted. In fact, land-use system is a complex system which is in association with economic development, environmental protection and ecological conservation (Lambin and Meyfroidt, 2010; Zhang et al., 2014). Therefore, various scenarios of violating environmental/ecological constraints and the tradeoff between economic development and environmental/ecological protection must be discussed.

Consequently, the objective of this study is to develop a hybrid LUA model to answer above challenges. The developed model which is called interval fuzzy chance-constrained land-use allocation (IFCC-LUA) model have two main advantages: first, it considers three uncertainties (discrete intervals, membership function and probability distribution function) simultaneously in a typical LUA system; second, it can systematically examine the comprehensive effects of economic development, environmental protection and ecological conservation in the LUA system and provide appropriate land use policies. The proposed model is applied to a LUA practice in Nanjing city, China. Interval solutions associated with different risk levels of constraint violation have been obtained. They can be used for generating decision alternatives and thus help decision makers identify desired land policies under various system-reliability constraints of economic development requirement, environmental capacity of pollutant and ecological equilibrium. Tradeoffs between system benefits and constraint violation risks can also be tackled. They are helpful for supporting (i) decision of land-use patterns and government land use policy, (ii) formulation of local policies regarding wastewater/solid waste discharge, environmental/ecological protection, and (iii) analysis of interactions among economic benefits, system reliability and pollutant discharges.

Methodology

Interval fuzzy chance-constrained programming

A general interval fuzzy chance-constrained programming (IFCCP) model is coupled with interval programming, chance constrained programming and fuzzy linear programming (Huang et al., 1994; Lee and Wen, 1996; Catalá et al., 2013; Zhou et al., 2013):

$$\text{Max} \quad f^{\pm} \cong C^{\pm}x^{\pm} \tag{1a}$$

subject to:

$$C^{\pm}x^{\pm} \gtrsim b^{\pm}_{opt} \tag{1b}$$

$$A_i^{\pm}x \lesssim b_i^{\pm} \quad i = 1, 2, \ldots, m, \quad i \neq s \tag{1c}$$

$$A_s^{\pm}x \lesssim b_s^{(p_s)} \quad s = 1, 2, \ldots, n, \quad s \neq i \tag{1d}$$