Spatial Optimization for Land Use Allocation: Accounting for Sustainability Concerns

Jing Yao[1§], Xiaoxiang Zhang[2], Alan T. Murray[3]

[1]Urban Big Data Centre, School of Social and Political Sciences, University of Glasgow, Glasgow, G12 8RZ, Scotland, UK

[2]Institute of Geographical Information Science and Engineering, Hohai University, Nanjing, Jiangsu, 210098, China

[3]Department of Geography, University of California at Santa Barbara, Santa Barbara, CA 93106, USA

E-mail addresses:

JY: Jing.Yao@glasgow.ac.uk

XZ: xiaoxiang@hhu.edu.cn

AM: amurray@ucsb.edu

[§]Corresponding author:

Urban Big Data Centre,

School of Social and Political Sciences,

University of Glasgow,

7 Lilybank Gardens,

Glasgow, G12 8RZ, Scotland, UK.

Tel.: +44 0141 3302368.

Spatial Optimization for Land Use Allocation:

Accounting for Sustainability Concerns

Abstract

Land use allocation has long been an important area of research in regional science. Land use patterns are fundamental to the functions of the biosphere, creating interactions that have substantial impacts on the environment. The spatial arrangement of land uses therefore has implications for activity and travel within a region. Balancing development, economic growth, social interaction and the protection of the natural environment is at the heart of long-term sustainability. Since land use patterns are spatially explicit in nature, planning and management necessarily must integrate geographical information system (GIS) and spatial optimization in meaningful ways if efficiency goals and objectives are to be achieved. This paper reviews spatial optimization approaches that have been relied upon to support land use planning. Characteristics of sustainable land use, particularly compactness, contiguity and compatibility, are discussed and how spatial optimization techniques have addressed these characteristics are detailed. In particular, objectives and constraints in spatial optimization approaches are examined.

Keywords: Land use planning, spatial optimization, sustainability, GIS, Land allocation

Introduction

Land is an essential component of human survival. Different uses of land help to fulfil human needs, involving both the manner of how land is modified, managed and maintained as well as the intended use (Turner et al., 1995). Land use arrangements are

fundamental to the functions of the biosphere because different uses (e.g. agriculture, forest, landfills, industrial land and residence) as well as their interactions have substantial impacts on the living environment and quality of life. Current land use arrangements are generally not efficient in terms of sustainable development, particularly in countries and regions experiencing rapid growth (Li and Liu, 2008; Demetriou et al., 2013a; Caparros-Midwood et al., 2015). Activities such as the overdevelopment of inner cities and reductions of agricultural land for urbanisation have deteriorated the environment, decreased biodiversity and fragmented land, all of which have intensified the conflict between economic growth and ecological protection. In order to consider and adopt sound options, it is essential to perform a systematic assessment of land use potential and alternatives in the context of economic and social conditions. Land use planning is important to local government, enabling them to mitigate conflicts and promote sound regional development. Land use planning integrating sustainable principles therefore is of great importance to society, with significant implications for the habitability of the earth.

The concept of sustainable development may be attributed to the United Nations Conference on the Human Environment in 1972. However, it was the release of the World Commission on Environment and Development (1987) that outlined the modern agenda for sustainable development, serving as a catalyst for the volume of literature that has followed. Sustainable development has a variety of interpretations, and they differ considerably. The World Commission on Environment and Development (1987) definition, “development that meets the needs of the present without compromising the

ability of future generations to meet their own needs", simply emphasizes the importance of inter-generation equity. The broad consensus is that sustainable development involves the achievement of social, economic and environmental outcomes with inter-generation equity. Accordingly, sustainable land use planning is intended to achieve long-term balanced development (and redevelopment, brownfield and blight cleanup, gentrification, etc.) among the economy, society, environment and ecosystem (Leccese and McCormick, 2000; Ligmann-Zielinska et al., 2008; Cao et al., 2012).

Since land use planning generally involves allocating various use activities to land parcels at a certain spatial scale, spatial optimization linking GIS and mathematical models has been increasingly applied to support the evaluation of planning activities (Church, 2001, 2002; Chen et al., 2010; Cao et al., 2011, 2012, 2014; Santé et al., 2016; Ligmann-Zielinska, 2017). Spatial optimization can be conceived of as the science of optimal spatial arrangement, which generally involves identification of the best locations for activities and resources with respect to objectives and constraining conditions (Church, 2001; Tong and Murray, 2012; Ligmann-Zielinska, 2017). In one respect, powerful spatial analysis functionality provided by GIS is well suited for land use planning. A well-known example is the work of McHarg (1969) seeking to identify the most suitable road corridor, doing so through comparison of map layers with different themes. This approach is now common functionality in GIS, often referred to simply as overlay. In another respect, optimization models based on linear programming and mixed-integer programming can mathematically express objectives and constraints involved in land use planning (Church, 2002). The quantity of land assigned to different

land uses as well as their best spatial arrangement can often be obtained using off-the-shelf optimization software tools to solve formulated models. Broadly speaking, spatial optimization for sustainable land use planning aims to allocate various land-use activities to land parcels in order to meet demand while satisfying the constraints imposed by the physical environment, society and economy (Ligmann-Zielinska et al., 2008).

Early interest in spatial optimization models to support land use planning can be found in the regional science literature (Isard, 1958; Marble, 1959; Herber and Stevens, 1960; Murray, 2017). Design (Schlager, 1965) and general urban planning (Bammi et al., 1976; Hopkins, 1977; Brotchie et al., 1980) can also be noted. Since the 1990s, with advances in GIS and computing, considerable effort has been devoted to land-use modelling that combines GIS and mathematical programming (Chuvieco, 1993; Batty and Densham, 1996). Operationally, this has often involved spatial decision support systems (SDSS) integrating multi-criteria optimization methods and GIS (Batty and Densham, 1996; Malczewski and Rinner, 2015; Sarkar et al., 2017). SDSS tools have also been developed to support the planning practice of various land use activities (Church et al. 2000; Ward et al. 2003; Stewart et al. 2004; Janssen et al., 2008; Arciniegas et al., 2011; Demetriou et al., 2013a; Porta et al., 2013; Dai and Ratick, 2014; Santé et al., 2016). Spatial optimization has been applied in a wide range of domains in relation to land use planning, such as reserve design (Nalle et al., 2002; Church et al., 2003; Fischer and Church, 2003; Dai and Ratick 2014; Önal et al., 2016; Jafari et al., 2017), land acquisition (Wright et al., 1983; Williams, 2002; Wu and Murray, 2008), waste landfill siting (Eiselt and Marianov,

2015), forest management (Church et al. 2000; John and Tóth, 2015) and urban and regional planning (Brookes, 2001; Ward et al., 2003; Caparros-Midwood et al., 2015).

The purpose of this paper is to review existing spatial optimization approaches to support land use allocation as well as to provide insights into emerging challenges. The next section introduces sustainability concerns in land use planning, highlighting spatial requirements such as compactness, contiguity and compatibility. Then, a range of spatial optimization models for land use allocation is detailed with a focus on mathematical specification. Extensions that address spatial criteria explicitly associated with sustainability are then detailed. This is followed by a discussion of challenges and potential for future research.

Land Use Planning and Sustainability Concerns

Land use planning involves evaluation and decision making about what activities should occur on particular parcels of land. “Land use is characterised by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it” (FAO and UNEP, 1999), and accordingly land use planning can be conceived as “the systematic assessment of land and water potential, alternatives for land use and economic and social conditions in order to select and adopt the best land-use options” (FAO, 1993). It is often employed by local government to manage and regulate land use activities, promoting efficiency and mitigating conflicts. Common land uses include residential, commercial, industrial, recreational, etc., and can be further grouped

depending on the intensity of use, such as high, medium or low (Ward et al., 2003). Actual planning practice, however, can vary from place to place depending on the underlying socio-economic and spatial context.

Since the late 1980s and early 1990s, new issues with regard to land use have arisen, largely due to worldwide rapid urbanization and continuing population growth, particularly in developing countries. For example, forest, grass and agriculture land uses have been reduced and transformed to industrial use in order to meet the needs of urban sprawl. Li and Yeh (2004) indicated that about 98,418 hectare of agricultural land (7.7% of the total land or 13.1% of the total agricultural land) has been lost in the core area of the Pearl River Delta, China, during 1988-1993 due to rapid urbanization and economic development. In addition, unbalanced development has resulted in serious impacts on the environment and ecosystem. For example, intensive land use and a lack of small landscapes, like field coppices, have been among the major reasons for a decline of the hare population in Germany (Meyer et al., 2009). As a result, sustainability has become an essential concern in the planning of land use activities.

Nevertheless, the concept of sustainability is ambiguous and difficult to define in operational terms. The emphasis of land use planning approaches has transitioned from balanced-quantities of each land use (e.g. Barber, 1976; Hopkins, 1977) to characteristic spatial layouts of different land uses (e.g. Williams, 2002; Ligmann-Zielinska et al., 2008; Cao et al., 2012). Of interest in this research are the spatial requirements associated with sustainable land use planning. Typical spatial criteria include contiguity, compactness

and compatibility. Contiguity reflects that a set of parcels is devoted to a particular land use, and would spatially denote the possibility of walking/traveling from a point to another point within a region only through parcels of the same use type (Cova and Church, 2000; Williams, 2002; Aerts et al, 2003; Ligmann-Zielinska et al., 2008; Jafari et al., 2017). Compactness is a spatial property of an allocated land use type where parcels are adjacent or close to each other, forming a roundish or circular shape (Aerts et al, 2003; Ligmann-Zielinska et al., 2008; Li et al., 2013). Although both contiguity and compactness favour proximity of the same land uses, the presence of one does not necessarily ensure the presence of the other. An example is given by Figure 1 with raster data consisting of grid cells. In Figure 1a, all the selected parcels (shaded area) for a particular land use are connected to ensure the site is not fragmented, though it is not compact given its long and narrow shape. In Figure 1b, the selected site for the land use activity is compact but lacking connectivity among the parcels. Finally, unlike contiguity and compactness, compatibility is a spatial property where neighbouring parcels have land uses that do not conflict. Representative of this situation would be a residence served by nearby supermarkets (retail), hospitals (health care), schools (education) and the like. Compatibility is commonly referred to as the degree to which the neighbouring land parcels of different land-use types can coexist without having negative influences on each other (Masoomi et al., 2013).

<Figure 1 about here>

In general, contiguous, compact and compatible clusters of land parcels are regarded as more sustainable than those that are fragmented and unconnected. For example,

contiguity enables social interaction, communication and transportation (Williams, 2002). Further, a more compact city requires lower energy usage, especially with respect to non-renewable resource consumption (Banister et al., 1997). Compact neighbourhoods in cities have better accessibility to public services and are more socially equitable (Watson, 2016) and compact green space has greater cooling potential (Zhang et al., 2017). Conservation biology suggests that contiguous and compact reserves are more effective for some species (Williams and ReVelle, 1996; Fischer and Church, 2003; Önal et al., 2016; Jafari et al., 2017). Industrial sites are more compatible with critical infrastructure, such as roads and power lines, and nearby access to qualified labour (Church et al. 2003). While widely accepted for guiding planning practice, these spatial characteristics present challenges for mathematical modelling. Specifically, explicitly incorporating spatial criteria in optimization models can be difficult.

Land Use Optimization

Addressing issues of sustainability in land use planning has been supported by the development and application of a range of spatial optimization models. Appropriate model specification involves care in defining objectives, identifying constraints and capabilities to solve associated models. While many different spatial optimization models have been developed, there are general characteristics that are commonly incorporated.

The simplest situation in land use planning is to select land for some purpose or an intended use, like an industrial business centre or a residential community. The knapsack

and threshold models reflect primary features of many planning approaches (Church and Murray, 2009).

Consider the following notation:

i: index of land parcels

a_i: benefit associated with land parcel i

c_i: acquisition cost associated with land parcel i

θ: total budget for land acquisition

L: required minimum benefit of acquired land

$$X_i = \begin{cases} 1 & \text{if land parcel } i \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

The knapsack problem is as follows:

$$\textit{Maximize} \qquad \sum_i a_i X_i \tag{1}$$

Subject to:

$$\sum_i c_i X_i \leq \theta \tag{2}$$

$$X_i = \{0,1\} \qquad \forall i \tag{3}$$

The objective (1) is to maximize the total benefit of land use. Constraint (2) limits the total cost of land acquisition by the budget. Constraints (3) require that decision variables are binary (0 or 1).

In contrast to the knapsack model, the threshold model seeks to minimize total cost while acquiring a certain amount of land as follows:

$$\textit{Minimize} \qquad \sum_i c_i X_i \tag{4}$$

Subject to:

$$\sum_i a_i X_i \geq L \tag{5}$$

$$X_i = \{0,1\} \qquad \forall i \tag{6}$$

The objective (4) is to minimize the total cost of land acquisition. Constraint (5) imposes a lower bound for the total benefit of the selected land. Constraints (6) are integer restrictions on decision variables.

Extension of these approaches is possible to account for additional land use types. Additional notation is as follows:

N: total number of land parcels

K: total number of land uses

i, j: index of land parcel, $i, j = 1,2,3,\ldots,N$

k: index of land-use type, $k = 1,2,3,\ldots,K$

a_{ik}: benefit associated with ith land parcel if it has land-use type k

s_i: area of land parcel i

c_{ik}: acquisition cost of land parcel i for land-use type k

θ_k: total budget for acquisition of land-use type k

US_k: upper bound of area for acquired land with type k

LS_k: lower bound of area for acquired land with type k

L_k : minimum benefit desired for land-use type k

$$X_{ik} = \begin{cases} 1 & \text{if land parcel } i \text{ is used for land-use type } k \\ 0 & \text{otherwise} \end{cases}$$

A general multi-type land-use planning problem is possible to structure as follows:

$$\textit{Maximize} \quad \sum_i \sum_k a_{ik} X_{ik} \tag{7a}$$

$$\textit{Minimize} \quad \sum_i \sum_k c_{ik} X_{ik} \tag{7b}$$

Subject to:

$$\sum_i c_{ik} X_{ik} \leq \theta_k \quad \forall k \tag{8}$$

$$\sum_i a_{ik} X_{ik} \geq L_k \quad \forall k \tag{9}$$

$$\sum_k X_{ik} = 1 \quad \forall i \tag{10}$$

$$\sum_i s_i X_{ik} \geq LS_k \quad \forall k \tag{11a}$$

$$\sum_i s_i X_{ik} \leq US_k \quad \forall k \tag{11b}$$

$$X_{ik} = \{0,1\} \quad \forall i, k \tag{12}$$

There are now two objectives, with objective (7a) reflecting a maximization of total benefit and objective (7b) reflecting minimization of total acquisition cost. This integrates and extends the knapsack and threshold objectives above, (1) and (4). Constraints (8) limits investment by land use type. Constraints (9) require a minimum level of benefit for each land use type. Constraints (10) restrict selection to only one land use assigned to each parcel. Constraints (11a) and (11b) impose lower and upper bounds on the total area for each land-use type. Constraints (12) require the decision variables to be integer.

This formulation can be considered an extension of the work of Aerts et al. (2003), where elements of both the threshold and knapsack approaches are integrated into one model. However, this goes beyond basic approaches to include multiple land use types.

Spatial Extensions

Church and Murray (2009) indicate that the knapsack and threshold models reflect underlying goals and objectives in land use planning. Interestingly, these models are aspatial in the sense that there are no geographic relationships explicitly tracked or accounted for, yet the basic decision is what land use activity should occur in a geographic area, a land parcel in this case. Spatial requirements, however, can be particularly important. Explicit consideration could include the shape of the selected area for a particular land use type, proximity to critical facilities, accessibility of undesirable services, etc. (Cova and Church, 2000; Ward et al., 2003; Ligmann-Zielinska et al., 2008; Cao et al., 2012; Caparros-Midwood et al., 2015; Önal et al., 2016; Jafari et al., 2017). Such criteria can be expressed as components of spatial optimization models, objectives, constraints or both. Compactness, contiguity and compatibility extensions are now detailed in the context of land use planning.

Compactness

An important concern in land use management is the compactness of parcels selected for a particular activity. As noted previously, compactness is a spatial property suggestive of parcels having the same land use type being adjacent or close to each other, forming a roundish or circular shape (Aerts et al, 2003; Ligmann-Zielinska et al., 2008; Li et al., 2013). Research has demonstrated that this property can be explicitly encouraged in the planning process when parcels are allocated land uses (Wright et al., 1983; Cova and Church, 2000; Nalle et al. 2002; Fischer and Church, 2003; Aerts et al. 2005; Dai and Ratick, 2014). Many strategies have been proposed to incorporate mathematical expressions in spatial optimization that promote compactness.

The most notable compactness approach is to use a shape index, often a function of perimeter-to-area ratio. Compactness is promoted by means of minimizing the index measure through the selection of parcels for the intended use. For example, Wright et al. (1983) employed the external perimeter of selected regions as an indicator of compactness.

$$\sum_{i=1}^{N} \sum_{j \in \Omega_i} b_{ij} Z_{ij} \tag{13}$$

where b_{ij} is the length of shared boundary between parcels i and j; $\Omega_i = \{j | j\text{th land parcel is adjacent to } i\text{th parcel}\}$; and Z_{ij} equals 1 if exactly one when either parcel i or j is selected and 0 otherwise. This measure may be incorporated into one of the above models as an objective to be optimized, provided that additional constraints are added to account for Z_{ij} relative to edge definition (see Wright et al. 1983, Church and Murray 2009). Indices similar to (13) have also been employed by McDonnell et al. (2002), Fischer and Church (2003) and Santé-Riveira et al. (2008). Other approaches have used the diagonal length of the minimum bounding rectangle (Gabriel et al., 2006) or weighted average ratio of area to perimeter square (Porta et al., 2013). In terms of multiple land-use types compactness has been approached through an average ratio of each land use (Janssen et al., 2008) or simply the mean perimeter-to-area ratio (Aerts et al., 2005). Shape indices can also be used to model parcel/site compactness, such as those proposed by Wentz (2000), Demetriou et al. (2013b) and Li et al. (2013).

Another alternative for modeling compactness utilizes the concept of core and buffer parcels, where core parcels are surrounded by buffer parcels of the same land-use type

(Williams and ReVelle, 1996; Aerts et al., 2003). Compactness is thus encouraged by minimizing the number of buffer parcels around core parcels, which would then be optimized as an objective function in one of the above models and accompanied by constraints defining core and buffer parcels of the same land use.

An extension of the above method is to allocate as many neighbouring parcels to the same land use as possible without explicitly distinguishing between core and buffer parcels. For example, Nalle et al. (2002) suggested maximizing the adjacencies between parcels for reserve network design. Aerts et al. (2003) proposed to maximize the number of neighbouring cells having the same land use for multi-site land-use allocation. More formally, a cluster can be defined as a set of contiguous parcels of the same land use. Thus, compactness can be accomplished by minimizing the total number of clusters of each land use or maximizing the largest cluster for each land-use type (Aerts et al., 2005; Ligmann-Zielinska et al., 2008; Janssen et al., 2008; Dai and Ratick 2014). For example, in the density based design constraint detailed in Ligmann-Zielinska et al. (2008), a land-use type can be assigned to a parcel if and only if the number of that parcel's neighbours of same land use is equal to or larger than a given threshold – the minimum number of parcels to form a cluster for a land use. A somewhat different approach is to minimize the number of aggregated blocks containing one land use, where blocks are defined as similar to clusters but they can overlap and include different land uses (Aerts et al., 2003). Nevertheless, such methods seek fewer and larger clusters/blocks of each land use, and thereby discourage fragmentation.

Stewart et al (2004) recognized a multi-faceted perspective of compactness, specifying three features that can be addressed: minimizing the number of clusters, maximizing the largest cluster for each land-use type, and maximizing a shape index for each land use defined as the average perimeter-to-area ratio across all clusters of the same land use. Such objectives have also been utilized in a goal-programming model (Aerts et al., 2005) and adopted within a GIS-based algorithm for land use planning (Stewart and Janssen, 2014).

Contiguity

Another important spatial property in land use planning is contiguity. Noted previously was that contiguity reflects a possibility of walking/traveling between two parcels of the same land use type while only going through other parcels of the same use type (Cova and Church, 2000; Williams, 2002; Aerts et al, 2003; Ligmann-Zielinska et al., 2008). Contiguity can be explicitly structured in spatial optimization models or implicitly accounted for in a solution algorithm. Most explicit approaches are based on graph theory imposing network connectivity (Cova and Church, 2000; Williams, 2002; Shirabe, 2005). Figure 2 shows the planar graph representation of the selected collection of parcels representing a site in Figure 1a. In Figure 2, each parcel in Figure 1a is abstracted to a vertex (also called a node) and the adjacent parcels are connected by an edge (also called an arc or link) between nodes, where parcels are considered adjacent to each other only if they share a common boundary.

<Figure 2 about here>

Based on the planar graph representation, Cova and Church (2000) proposed a set of path-based contiguity constraints for a single site search problem, which was extended by Duque et al. (2011) as order-based parcel selection conditions to form contiguous regions. The essential condition is that any parcel to be included in a region must have a path consisting of selected parcels to the predefined root parcel of that region. Williams (2002) defined necessary and sufficient conditions for spatial connectivity. The key procedure is to generate spanning trees in both primal and dual graphs taking advantage of the primal-dual structure of planar graphs. Thus, a contiguous site search problem can be addressed by finding an optimal subtree of a spanning tree within a planner graph.

Rather than utilizing paths and spanning trees, Shirabe (2005, 2009) formulated contiguity constraints based on network flows. Similar to the concept of “root” parcel in Cova and Church (2002), Shirabe (2005) defined a unique “sink” parcel for a sub-network (selected region) such that contiguity is ensured by requiring any flow emanating from other “sources” (parcels) can arrive at the “sink” through the edges within that sub-network. Unlike the “root”, the “sink” does not need to be pre-specified, but an alternative reduced formulation can be obtained if both the “sink” and the maximum number of parcels to be contained in that region is pre-defined (Shirabe, 2005). This work was extended by Duque et al. (2011) to include multiple network flows, one for each region. These conditions can be readily incorporated into the above models to ensure contiguity among selected parcels.

Also based on graph theory, a relative measure of contiguity insensitive to shapes was developed by Wu and Murray (2008). It can be simply defined as the ratio of actual and maximum possible contiguity linkages. A relative measure is useful because it is often not easy to achieve complete contiguity (as shown in Figure 1a) and the real landscape is often fragmented (Williams, 2002).

Compatibility

A goal of sustainable land use planning is minimal conflict between neighbouring land uses, avoiding situations where land use benefits are degraded because of nearby activities. As defined above, compatibility is a spatial property where neighbouring parcels have land uses that do not conflict (Masoomi et al., 2013). Compatibility is concerned with the relationships among various land-use types and the overall land-use pattern. Generally, compatibility has been approached by either quantitative indices or mathematical modelling.

In sustainable land use planning, compatibility scores or indices are usually employed to quantify and represent the compatibility of a pair of land uses. Those measures can be derived using approaches such as Delphi method and analytic hierarchy process (AHP), which are both relied upon experts' opinions. Specifically, the former collects experts' answers for questionnaires in a few rounds and arrives at a final decision when the answers converge according to some criteria; the latter decomposes the problem into a hierarchy of sub-problems, each having an associated weight based on which alternative solutions are assessed. In the practice of land use planning, Cao et al. (2011) calculated

the relative compatibilities for pairs of land uses with the AHP technique. Under a framework of the Delphi method, Masoomi et al. (2013) constructed a matrix containing the compatibility indices of each land-use type to all the other land-use types. As a result, the goal of compatibility has often been represented as objective functions in spatial optimization models, such as maximizing compatibility (Cao et al., 2011; Liu et al., 2013; Masoomi et al., 2013) or minimizing incompatibility (Ligmann-Zielinska et al., 2008; Haque and Asami, 2011, 2014).

A situation where two land uses are not compatible suggests that parcels not be allocated these two uses when they are adjacent to each other. That is, if a land parcel is selected for one land use, its adjacent parcels should not be chosen for the other land use. This condition can be structured as follows:

$$X_{ik} + X_{jt} \leq 1 \tag{14}$$

where parcels i and j are adjacent (or neighbors) and their respective land use types, k and t, are incompatible. This type of constraint has been widely adopted in location problems involving conflicting land uses, such as harvest scheduling problems (Murray, 1999; John and Tóth, 2015). Alternative constraint formulation techniques are discussed in Murray and Kim (2008).

Solution Methods

In light of the discussion above, mathematically formulating sustainable land use planning problems can be complex, particularly when spatially explicit criteria are taken

into account. Solving such problems, however, can be even more challenging. One reason is that land use planning generally involves multiple and often competing objectives, such as minimizing development costs and negative environment impacts, and maximizing economic and ecological benefits, among others. The multi-objective concerns are rooted in the multi-faceted nature of land use planning activities and interests among various stakeholders, such as conservation organizations, government agencies, developers, forestry companies, etc. Any solution method, either exact or heuristic, therefore must account for the trade-offs and interactions among multiple objectives raised in land use planning.

There are a number of strategies dealing with multiple objectives. Of interest, of course, is simultaneously accounting for all objectives, giving the so-called Pareto frontier (Pareto, 1971). Solutions on the frontier are also called non-inferior, and represent cases where you cannot improve one objective without sacrificing the performance of at least one other objective (Cohon, 1978). Many approaches have sought non-inferior solutions for land use planning (e.g. Duh and Brown, 2007; Huang et al., 2013; Masoomi et al., 2013; Cao et al., 2014). However, depending on the problem formulation, number of objectives and the competing nature of objectives, deriving all non-inferior solutions may be difficult. An approach often utilized is to transform multiple objectives into one single objective, where each objective has an associated weight representing its relative importance (e.g. Gabriel et al., 2006; Santé-Riveira et al., 2008; Chen et al., 2010; Haque and Asami, 2011, 2014; Liu et al., 2013). This enables some non-inferior solutions to be found, but not necessarily all, if an appropriate range of weights can be found.

Beyond the issue of multiple objectives is whether a spatial optimization problem can be solved in the first place, either by exact algorithms or heuristics. Exact algorithms are the approaches that can ensure the identification of the best solution. That is, the optimal solution found by an exact method can be proved better than any other feasible solution regarding objective values. Common exact approaches include enumeration, linear programming, integer programming with brunch-and-bound. In land use planning, branch-and-bound has been employed by Cova and Church (2000) and Ligmann-Zielinska et al. (2008). The advantage of exact algorithms is that they can guarantee optimal solutions and usually can be carried out in a number of the off-the-shelf software such as AMPL, LINDO, CPLEX, and Gurobi. With regard to land use planning, however, increased problem size and integer constraints on decision variables are major barriers to generate rapid solutions.

Heuristics are often effective alternatives capable of handling large land use optimization problems. They start from an initial solution and search for improved solutions in an iterative way using some strategies until certain criteria are satisfied. Compared to exact methods, heuristics have the advantage of the ability of handling a larger volume of land parcels, as well as solving the optimization problems much more quickly yet generating satisfactory solutions. Such solutions might be optimal, but more often they are near optimal or sufficiently good for underlying planning context. Heuristics are widely employed when exact methods are extremely hard, if not impossible, to develop or implement due to limitation in current computing environment. Common heuristics that

have been applied in land use optimization problems include region-growing (Brookes, 2001; Church et al., 2003), genetic algorithms (Brookes, 2001; Stewart et al., 2004; Aerts et al., 2005; Janssen et al., 2008; Cao et al., 2011, 2012; Haque and Asami, 2011, 2014; Porta et al. 2013; Cao et al., 2014; Demetriou et al., 2013a; Stewart and Janssen, 2014; Caparros-Midwood et al., 2015; Li and Parrott, 2016), simulated annealing (Aerts and Heuvelink, 2002; McDonnell et al. 2002; Nalle et al., 2002; Aerts et al., 2005; Duh and Brown, 2007; Santé-Riveira et al., 2008; Caparros-Midwood et al., 2015; Santé et al., 2016), evolutionary algorithms (Dai and Ratick, 2014; Karakostas, 2016), particle swarm optimization (Liu et al., 2013; Masoomi et al., 2013; Liu et al., 2015; Zhang et al., 2016) and artificial immune system (Huang et al., 2013), among others. For example, Mi et al. (2015) integrated a genetic algorithm with an ant colony algorithm to support land-use allocation in a limited development ecological zone in Ningxia, China. Caparros-Midwood et al. (2015) implemented both genetic algorithm and simulated annealing to identify various trade-off urban development plans for Middlesbrough in the UK and found that the former is superior in terms of solution time and the capability of finding better solutions. Instead of using single heuristics, Mohammadi et al. (2016) proposed three hybrid meta-heuristics and found the one involving GRASP, genetic algorithm and Tabu search was most efficient in solving real problems.

Addressing contiguity is an example of where a group of heuristics has generally been relied upon with much success in land use planning. The parameterized region-growing heuristic proposed by Brookes (2001) starts with a seed parcel and expands the region by iteratively adding adjacent parcels until the required size of the region is achieved.

Similarly, the patch-growing process developed by Church et al. (2003) also generates a region with a starting seed parcel, which was incorporated into a multilevel modeling framework by Meentemeyer et al. (2013) to simulate the dynamics of land development. However, these approaches differ in terms of the rules guiding the region growth. For example, parameterized region-growing adds one parcel at a time according to the shape and land-use suitability criteria, while patch-growing process adds a proportion of parcels from a candidate list relying on the composite suitability. Unlike the above two approaches where the seed parcels are pre-specified, the seed patches are generated automatically in the multiple-criteria heuristic method by Vanegas et al. (2008).

In addition, some efforts have attempted to generate alternative planning scenarios by simulation approaches that are commonly adopted to model spatial processes such as urban sprawl and land use/land cover changes. For example, Cao et al. (2014) used a genetic algorithm to provide robust parameters for a cellular automata model to understand the rural–urban land conversion in Delaware, USA. Zhang et al. (2016) used multi-agent systems to simulate spatial allocation of land uses in Changsha, China.

Discussion

As can be seen from the above descriptions, land use planning problems have unique spatial characteristics which can be addressed by spatial optimization approaches. However, providing appropriate systematic approaches and tools that aid the decision-making process associated with sustainable land use planning is an enormous and

complex task. Land use planning is a multi-faceted process spanning several disciplines including demography, management science, ecological economics, landscape planning, sustainable development and geography. The planning activities usually involve integrated multidisciplinary analysis for appraising development proposals and generating alternative future scenarios. Not surprisingly, the inherent complexity and multifaceted nature of sustainable land use planning poses challenges to spatial optimization, such as mechanisms for creating and integrating information and model inputs from a range of discipline areas, interactive and user friendly analysis systems for developing and evaluating land use planning alternatives, and determining appropriate scales of analysis and so on. Some of the concerns in developing integrated planning approaches will be discussed in the remainder of this section, including evaluation of planning scenarios, computational efficiency, integration with GIS and temporal dimension.

Firstly, some quantitative measures can be employed to compare the overall performance of different solutions for land use planning. Since land use activities have potential impacts on society, environment and ecosystems, measures like spatial landscape indices (Uuemaa et al., 2013) can be used to evaluate various spatial patterns of land uses with regard to landscape structure and how well that landscape can support ecosystem functions or ecologic sustainability (Huang, et al., 2015).

Attention should also be paid to different requirements on spatial characteristics of obtained sites by diverse land uses. Since a single formulation is typically employed for a

particular spatial criterion regardless of the land-use types, it is necessary to verify whether the criterion is suitable for each land use. For example, connectivity is no doubt required for transportation land use for which compactness is often not a significant concern because roads or railways always have a linear shape. As for reserve selection, both contiguity and compactness are essential in terms of promoting ecologic sustainability (Önal et al., 2016).

Secondly, land use planning problems are intrinsically complex and most of the existing work has been constrained in one way or the other due to computational difficulties. One important reason is that defining spatial criteria such as connectivity, compactness and compatibility involves various manipulation, query and processing of spatial data, as well as evaluation of spatial relationships such adjacency and proximity. Although most research has taken advantage of the raster data structure to simplify spatial operations like spatial query and distance measuring, different raster schemes of the same study area can add to the uncertainty in the ultimate land use allocation. Also, incorporation of spatial criteria usually implies additional objectives, constraints and/or decision variables, thus leading to complex models requiring more computational efforts.

In order to improve computational efficiency, on one hand, simplified but enhanced model structure with reduced problem size can be developed by new spatial modelling techniques. Likewise, novel solution algorithms, particularly the heuristics, have great potential to improve the solving procedure. On the other hand, remarkable advances in computer and information technologies in recent years have provided great opportunities

for computing tasks involving large datasets. For example, Santé et al. (2016) proposed a simulated annealing heuristic for land use allocation using parallel computing.

Thirdly, as land use planning is inherently a spatial problem, the importance of integrating GIS and the planning practice has been widely recognized (Church and Murray, 2009). Generally, GIS and optimization solvers are either loosely or tightly coupled to support the decision process in relation to land use planning. In the loosely coupled system, the communication between GIS and optimization routines is commonly realized through file exchange. The tight integration usually implements GIS functionality and problem solving procedure in a unified computing environment. Recent researches have stressed the importance of interactive decision-making processes which require, based on feedback from decision makers, rapid generation of various planning scenarios as well as flexible model adjustment (Janssen, et al., 2015).

Recently, the open source initiatives[1] have offered great opportunities and flexibility to develop new software tools for land use optimization problems. Open source software is usually developed by collaborations and can be used, changed and shared for free, thereby facilitating and encouraging the adoption and use of various research methodologies (Jackson et al., 2017). Although recent years have seen an extensive growth in both open source GIS software tools (e.g. QGIS[2]) and open source optimization tools (e.g. COIN-OR[3] and Liger[4]), there are few software tools available in

[1] http://opensource.org/
[2] http://www.qgis.org
[3] http://www.coin-or.org
[4] http://codem.group.shef.ac.uk/index.php/liger

the field of spatial optimization combining GIS and operations research. Given the rapid progress in the open source movement, open source software supporting spatial optimization in general and sustainable land use planning in particular is worth further research efforts.

Finally, an element that has attracted less attention in sustainable land use planning is the temporal dimension. The essential concern in time dependent land use planning is that "which parcels" are used for "what purpose" at "what time" (Ligmann-Zielinska, 2017). To date, most spatial optimization models for sustainable land use planning are designed to answer the first two questions, assuming that all the decisions are made at one time. One exception is the work on timber harvests scheduling which concerns spatial harvesting patterns over a multi-period time horizon (John and Tóth, 2015). As attributes of land parcels and interactions among different land uses vary across both space and time, incorporation of temporal dimension and development of spatially-temporally explicit optimization models are critical to the long-term planning practice of sustainable land use.

Conclusions

Worldwide urbanization has brought dramatic changes to physical environment and human society, particularly in the developing countries and regions. Meanwhile, the increasing demand for land resources due to growth in population, urban areas and economy has posed great challenges to rural and urban sustainable development.

Sustainable land use planning is an effective way to promote socioeconomic and environmental sustainability. Most principles in sustainable land use planning are inherently spatial, and GIS-coupled spatial optimization provides useful tools to support the planning practice of sustainable land use. This paper has reviewed spatial optimization approaches commonly employed in the relevant area, mainly focusing on the spatial criteria required by sustainable development. Hopefully, this work would encourage the use of spatial optimization models tailored to particular planning context, and ultimately assist decision-makings pertaining to sustainable development.

References

Aerts, J. C. J. H. and Heuvelink, G. B. M. 2002. Using simulated annealing for resource allocation. *International Journal of Geographic Information Science*, 16(6): 571-587.

Aerts, J. C. J. H., Eisinger, E., Heuvelink, G. B. M., and Stewart, T. J. 2003. Using linear integer programming for multi-site land-use allocation. *Geographical Analysis*, 35(2): 148-169.

Aerts, J. C. J. H, Herwijnen, M. V., Janssen, R., and Stewart, T. J. 2005. Evaluating spatial design techniques for solving land-use allocation problems. *Journal of Environmental Planning and Management*, 48(1): 121-142.

Arciniegas, G. A., Janssen, R., and Omtzigt, N. 2011. Map-based multicriteria analysis to support interactive land use allocation. *International Journal of Geographical Information Science*, 25(12): 1931-1947.

Barber, G. 1976. Land-use plan design via interactive multi-objective programming. *Environment and Planning A*, 8: 239-45.

Bammi, D., Bammi, D., and Paton, R. 1976. Urban planning to minimize environmental impact. *Environment and Planning A*, 8: 245-259.

Banister, D., Watson, S., and Wood, C. 1997. Sustainable cities: transport, energy, and urban form. *Environment and Planning B: Planning and design*, 24: 125-144.

Batty, M. and Densham, P. J. 1996. Decision support, GIS, and urban planning. *Sistema Terra*, 5(1): 72-76.

Brookes, C. J. 2001. A genetic algorithm for designing optimal patch configurations in GIS. *International Journal of Geographical Information Science*, 15(6): 539-559.

Brotchie, J., Dickey, J. and Sharpe, R. 1980. *TOPAZ – General Planning Technique and its Application at the Regional, Urban and Facility Planning Level* (Berlin: Springer-Verlag).

Cao, K., Batty, M., Huang, B., Liu, Y., Yu, L., and Chen, J. 2011. Spatial multi-objective land use optimization: extensions to the Non-Dominated Sorting Genetic Algorithm-II. *International Journal of Geographical Information Science*, 1(21): 1–21.

Cao, K., Huang, B., Wang, S., and Lin, H. 2012. Sustainable land use optimization using boundary-based fast genetic algorithm. *Computers, Environment and Urban Systems*, 36: 257–269.

Cao, K., Huang, B., Li, M., and Li, W. 2014. Calibrating a cellular automata model for understanding rural–urban land conversion: a Pareto front-based multi-objective

optimization approach. *International Journal of Geographical Information Science*, 28(5): 1028-1046.

Caparros-Midwood, D., Barr, S. and Dawson, R. 2015. Optimised spatial planning to meet long term urban sustainability objectives. *Computers, Environment and Urban Systems*, 54: 154-164.

Chen, Y., Li, X., Liu, X., and Liu, Y. L. 2010. An agent-based model for optimal land allocation (AgentLA) with a contiguity constraint. *International Journal of Geographical Information Science*, 24: 1269–1288.

Church, R. L. 2001. Spatial optimization models. In Smelser N.J. and Baltes, P.B. (eds.) *International Encyclopedia of the Social & Behavioral Sciences*, New York: Elsevier. pp. 14,811–18.

Church, R. L. 2002. Geographical information systems and location science. *Computers & Operations Research*, 29: 541-562.

Church, R. L. and Cova, T. J. 2000. Mapping evacuation risk on transportation networks using a spatial optimization model. *Transportation Research* C, 8: 321–336.

Church, R. L., Gerrard, R. A., Gilpin, M., and Stine, P. 2003. Constructing cell-based habitat patches useful in conservation planning. *Annals of the Association of American Geographers*, 93(4): 814–827.

Church, R. L. and Murray, A. T. 2009. *Business Site Selection, Location Analysis and GIS*. Wiley, New York.

Church, R. L., Murray, A. T., Figueroa, M. A., and Barber, K. H. 2000. Support system development for forest ecosystem management. *European Journal of Operational Research*, 121: 247-258.

Chuvieco, E. 1993. Integration of linear programming and GIS for land-use modeling. *International Journal of Geographical Information Systems*, 7: 71-83.

Cohon, J. L. 1978. *Multi-objective Programming and Planning*. New York, Academic Press.

Cova, T. J. and Church R. L. 2000. Contiguity constraints for single-region site search problems. *Geographical Analysis*, 32, pp.306-329.

Dai, W. and Ratick, S. J. 2014. Integrating a raster geographical information system with multi-objective land allocation optimization for conservation reserve design. *Transactions in GIS*, 18(6): 936-949.

Demetriou, D., See, L., and Stillwell, J. 2013a. A spatial genetic algorithm for automating land partitioning. *International Journal of Geographical Information Science*, 27: 2391–2409.

Demetriou, D., See, L., and Stillwell, J. 2013b. A parcel shape index for use in land consolidation planning. *Transactions in GIS*, 17(6): 861-882.

Duh, J. D. and Brown, D. G. 2007. Knowledge-informed pareto simulated annealing for multi-objective spatial allocation. *Computers, Environment and Urban Systems*, 31: 235–281.

Duque, J.C., Church, R.L. and Middleton, R.S., 2011. The *p*-Regions Problem. *Geographical Analysis*, 43(1): 104-126.

Eiselt, H.A. and Marianov, V. 2015. Location modeling for municipal solid waste facilities. *Computers & Operations Research*, 62: 305-315.

FAO. 1993. *Guidelines for land-use planning*. Development documents series. Food and Agriculture Organization of the United Nations.

FAO. 1999. Land use. http://www.fao.org/nr/land/use/en/

Fischer, D. T. and Church, R. L. 2003. Clustering and compactness in reserve site selection: an extension of the biodiversity management area selection model. *Forest Science*, 49(4): 555-565.

Gabriel, S. A., Faria, J. A., and Moglen, G. E. 2006. A multiobjective optimization approach to smart growth in land development. *Socio-Economic Planning Sciences*, 40: 212–248.

Haque, A. and Asami, Y. 2011. Optimizing urban land-use allocation: case study of Dhanmondi Residential Area, Dhaka, Bangladesh. *Environment and Planning B: Planning and Design*, 38: 388–410.

Haque, A. and Asami, Y. 2014. Optimizing urban land use allocation for planners and real estate developers. *Computers, Environment and Urban Systems*, 46: 57-69.

Herbert, J. D. and Stevens, B. H. 1960. A model for the distribution of residential activity in urban areas. *Journal of Regional Science*, 2(2): 21-36.

Hopkins, L. D. 1977. Land-use design-quadratic assignment and central facility models. *Environment and Planning A*, 9: 625-642.

Huang, K. N., Liu, X., Li, X., Liang, J., and He, S. 2013. An improved artificial immune system for seeking the Pareto front of land-use allocation problem in large areas. *International Journal of Geographical Information Science*, 27: 922–946.

Huang, L., Wu, J. and Yan, L. 2015. Defining and measuring urban sustainability: a review of indicators. *Landscape Ecology*, 30(7): 1175-1193.

Isard, W. 1958. Interregional linear programming: an elementary presentation and a general model. *Journal of Regional Science*, 1(1): 1-59.

Jackson, R., Rey, S. and Járosi, P. 2017. Object Orientation, Open Regional Science, and Cumulative Knowledge Building. In *Regional Research Frontiers* - Vol. 2, R. Jackson, P. Schaeffer (eds.), 259-291 (Springer) - DOI 10.1007/978-3-319-50590-9_16.

Jafari, N., Nuse, B.L., Moore, C.T., Dilkina, B. and Hepinstall-Cymerman, J. 2017. Achieving full connectivity of sites in the multiperiod reserve network design problem. *Computers & Operations Research*, 81: 119-127.

Janssen, R., Arciniegas, G. and Alexander, K.A. 2015. Decision support tools for collaborative marine spatial planning: identifying potential sites for tidal energy devices around the Mull of Kintyre, Scotland. *Journal of Environmental Planning and Management*, 58(4): 719-737.

Janssen, R., van Herwijnen, M., Stewart, T. J., and Aerts, J. C. J. H. 2008. Multiobjective decision support for land use planning. *Environment and planning B: Planning and design*, 35: 740–756.

John, R.S. and Tóth, S.F. 2015. Spatially explicit forest harvest scheduling with difference equations. *Annals of Operations Research*, 232(1), pp: 235-257.

Karakostas, S.M. 2016. Land-use planning via enhanced multi-objective evolutionary algorithms: optimizing the land value of major Greenfield initiatives. *Journal of Land Use Science*, 11(5): 595-617.

Leccese, M., and Mccormick, K. (Eds). 2000. *Charter of the New Urbanism* (New York: McGraw-Hill).

Li, W., Goodchild, M. F., and Church, R. 2013. An efficient measure of compactness for two-dimensional shapes and its application in regionalization problems. *International Journal of Geographical Information Science*, 27(6): 1227-1250.

Li, X. and Liu, X. 2008. Embedding sustainable development strategies in agent-based models for use as a planning tool. *International Journal of Geographical Information Science*, 22: 21–45.

Li, X. and Parrott, L. 2016. An improved Genetic Algorithm for spatial optimization of multi-objective and multi-site land use allocation. *Computers, Environment and Urban Systems*, 59: 184-194.

Li, X. and Yeh, A. G. O. 2004. Analyzing spatial restructuring of land use patterns in a fast growing region using remote sensing and GIS. *Landscape and Urban planning*, 69(4): 335–354.

Ligmann-Zielinska, A., Church, R. L., and Jankowski, P. 2008. Spatial optimization as a generative technique for sustainable multiobjective land-use allocation. *International Journal of Geographical Information Science*, 22(6): 601-622.

Ligmann-Zielinska, A. 2017. Spatial Optimization. *The International Encyclopedia of Geography*. 1-6.

Liu, X., Ou, J., Li, X., and Ai, B. 2013. Combining system dynamics and hybrid particle swarm optimization for land use allocation. *Ecological Modelling*, 257: 11–24.

Liu, Y., Tang, W., He, J., Liu, Y., Ai, T. and Liu, D. 2015. A land-use spatial optimization model based on genetic optimization and game theory. *Computers, Environment and Urban Systems*, 49: 1-14.

Malczewski, J. and Rinner, C. 2015. *Multicriteria Decision Analysis in Geographic Information Science*. Springer Berlin Heidelberg.

Marble, D. F. 1959. Transport inputs at urban residential sites. *Papers in Regional Science*, 5(1): 253-266.

Masoomi, Z., Mesgari, M. S., and Hamrah, M. 2013. Allocation of urban land uses by multi-objective particle swarm optimization algorithm. *International Journal of Geographical Information Science*, 27(3): 542-566,

Meyer, B. C., Lescot, J. M., and Laplana, R. 2009. Comparison of two spatial optimization techniques: a framework to solve multiobjective land use distribution problems. *Environmental management*, 43(2): 264-281.

McDonnell, M. D, Possingham, H. P, Ball, I. R, and Cousins, E. A. 2002. Mathematical methods for spatially cohesive reserve design. *Environmental Modeling and Assessment*, 7: 107–14.

McHarg, I.L. 1969. *Design with nature*. Garden City, NY: The Natural History Press.

Meentemeyer, R.K., Tang, W., Dorning, M.A., Vogler, J.B., Cunniffe, N.J. and Shoemaker, D.A. 2013. FUTURES: multilevel simulations of emerging urban–rural landscape structure using a stochastic patch-growing algorithm. *Annals of the Association of American Geographers*, 103(4): 785-807.

Mi, N., Hou, J., Mi, W. and Song, N. 2015. Optimal spatial land-use allocation for limited development ecological zones based on the geographic information system and a genetic ant colony algorithm. *International Journal of Geographical Information Science*, 29(12): 2174-2193.

Mohammadi, M., Nastaran, M. and Sahebgharani, A. 2016. Development, application, and comparison of hybrid meta-heuristics for urban land-use allocation optimization: Tabu search, genetic, GRASP, and simulated annealing algorithms. *Computers, Environment and Urban Systems*, 60: 23-36.

Murray, A. T. 1999. Spatial restrictions in harvest scheduling. *Forest Science*, 45(1): 45-52.

Murray, A. T. 2017. Regional Analytics. *Annals of Regional Science*, 59: 1-13.

Murray, A. T. and Kim, H. 2008. Efficient identification of geographic restriction conditions in anti-covering location models using GIS. *Letters in Spatial and Resource Sciences* 1: 159-169.

Nalle, D. J., Arthur, J. L., and Sessions J. 2002. Designing compact and contiguous reserve networks with a hybrid heuristic algorithm. *Forest Science*, 48(1): 99-105.

Önal, H., Wang, Y., Dissanayake, S.T. and Westervelt, J.D. 2016. Optimal design of compact and functionally contiguous conservation management areas. *European Journal of Operational Research*, 251(3): 957-968.

Pareto, V. 1971. *Manual of political economy* (Augustus M. Kelley, New York) translated from French edition of 1927 by Ann S. Schwier, first published in 1896.

Porta, J., Parapar, J., Doallo, R., Rivera, F.F., Santé, I., and Crecente, R. 2013. High performance genetic algorithm for land use planning. Computers, *Environment and Urban Systems*, 37: 45–58.

Santé, I., Boullón, M., Crecente, R., and Miranda, D. 2008. Algorithm based on simulated annealing for land-use allocation. *Computers and Geosciences*, 34: 259-268.

Santé, I., Pacurucu, N., Boullón, M., García, A.M. and Miranda, D. 2016. An open source GIS-based Planning Support System: Application to the land use plan of La Troncal, Ecuador. *Transactions in GIS*, 20(6): 976-990.

Santé, I., Rivera, F.F., Crecente, R., Boullón, M., Suárez, M., Porta, J., Parapar, J. and Doallo, R. 2016. A simulated annealing algorithm for zoning in planning using parallel computing. *Computers, Environment and Urban Systems*, 59: 95-106.

Sarkar, S., Dyer, J.S., Margules, C., Ciarleglio, M., Kemp, N., Wong, G., Juhn, D. and Supriatna, J. 2017. Developing an objectives hierarchy for multicriteria decisions on land use options, with a case study of biodiversity conservation and forestry production from Papua, Indonesia. *Environment and Planning B: Urban Analytics and City Science*, 44(3): 464-485.

Schlager, K. J. (1965). A land use plan design model. *Journal of the American Institute of Planners*, 31(2), 103-111.

Shirabe, T. 2004. Towards a temporal extension of spatial allocation modeling. In *GIScience 2004*, LNCS 3234 M.J. Egenhofer, C. Freksa, and H.J. Miller (Eds), pp. 285–298 (Berlin: Springer).

Shirabe, T. 2005. A model of contiguity for spatial unit allocation. *Geographical Analysis*, 37: 2–16.

Shirabe, T. 2009. Districting modeling with exact contiguity constraints. *Environment and planning B, Planning and Design*, 36: 1053-1066.

Stewart, T. J., Janssen, R., and van Herwijnen, M. 2004. A genetic algorithm approach to multiobjective land use planning. *Computers and Operations Research*, 32: 2293–2313.

Stewart, T. J. and Janssen, R. 2014. A multiobjective GIS-based land use planning algorithm. *Computers, Environment and Urban Systems*, 46: 25-34.

Tong, D. and Murray, A. T. 2012. Spatial optimization in geography. *Annals of the Association of American Geographers*, 102(6): 1290-1309.

Turner, B. L., Skole, D., Sanderson, S., Fischer, G., Fresco, L., and Leemans, R. 1995. *Land-use and land-cover change; science/research plan*. IGBP Report No. 35, HDP Report No. 7. IGBP and HDP, Stockholm and Geneva.

Uuemaa, E., Mander, Ü. and Marja, R. 2013. Trends in the use of landscape spatial metrics as landscape indicators: a review. *Ecological Indicators*, 28: 100-106.

Vanegas, P., Cattrysse, D., and Van-Orshoven, J. 2008. Comparing exact and heuristic methods for site location based on multiple attributes: an afforestation application. *Lecture Notes in Computer Science*, 5072: 389–404.

Ward, D. P., Murray, A. T., and Phinn, S. R. 2003. Integrating spatial optimization and cellular automata for evaluating urban change. *Annals of Regional Science*, 37: 131-148.

Watson, V. 2016. Locating planning in the New Urban Agenda of the urban sustainable development goal. *Planning Theory*, 15(4): 435-448.

WCED. 1987. *Our common future*. Oxford: Oxford University Press.

Wentz, E. A. 2000. A shape definition for geographic applications based on edge, elongation, and perforation. *Geographical Analysis*, 32(2): 95–112.

Williams, J. C. and ReVelle, C. S. 1996. A 0 - 1 programming approach to delineating protected reserves. *Environmental Planning B*, 23: 607-24.

Williams, J. C. 2002. A zero-one programming model for contiguous land acquisition. *Geographical Analysis*, 34(4): 330-349.

Williams, K., Burton, E., and Jenks, M, (ed). 2000. *Achieving Sustainable Urban Form*. E & FN Spon, Taylor & Francis, London.

Wright, J., ReVelle, C. S., and Cohon, J. 1983. A muti objective integer programming model for the land acquisition problem. *Regional Science and Urban Economics*, 12: 31-53.

Wu, X. and Murray, A. T. 2008. A new approach to quantifying spatial contiguity using graph theory and spatial interaction. *International Journal of Geographical Information Science*, 22: 387–407.

Zhang, Y., Murray, A. T., and Turner, B. L. 2017. Optimizing green space locations to reduce surface urban heat island effects in Phoenix, Arizona: an integrated modeling framework. *Landscape and Urban Planning*, 165: 162-171.

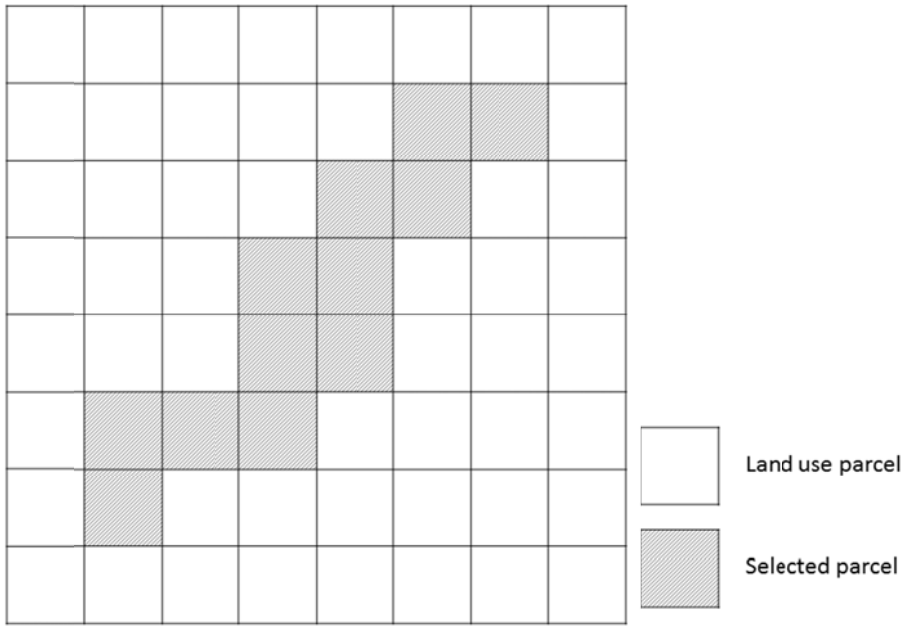
Zhang, H., Zeng, Y., Jin, X., Shu, B., Zhou, Y. and Yang, X. 2016. Simulating multi-objective land use optimization allocation using Multi-agent system—A case study in Changsha, China. *Ecological Modelling*, 320: 334-347.

Figure 1 Examples of contiguous and compact sites. (a) A contiguous site; (b) A compact site

Figure 2 The planar graph representation of the selected site in Figure 1(a)

Figure 1 Examples of contiguous and compact sites. (a) A contiguous site; (b) A compact site

(a)



(b)

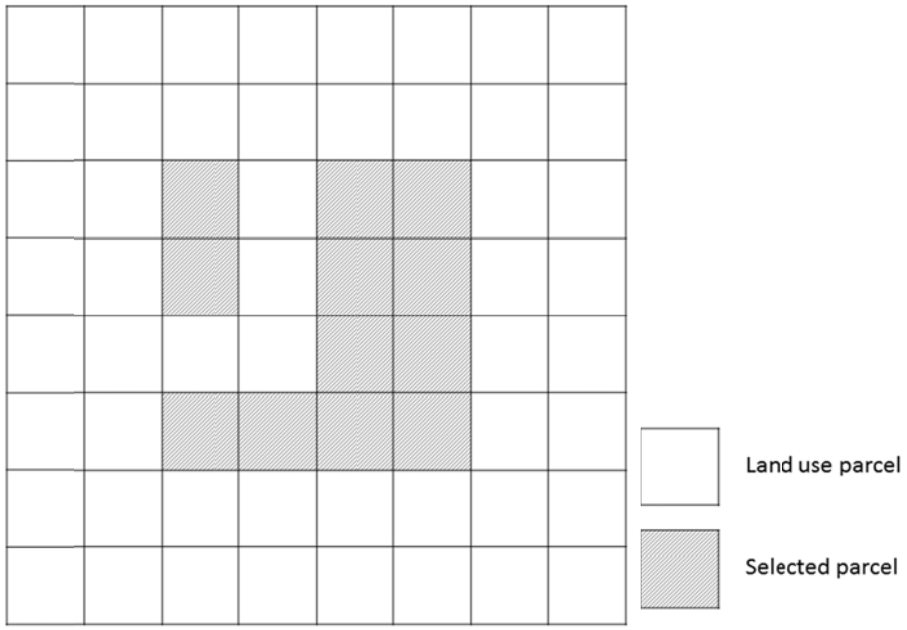


Figure 2 The planar graph representation of the selected site in Figure 1a