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Innovative Applications of O.R.

A new method to solve the fully connected Reserve Network Design Problem

Nahid Jafari *, John Hearne

School of Mathematical and Geospatial Sciences, RMIT University, Australia

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ABSTRACT

In selecting sites for conservation purposes connectivity of habitat is important for allowing species to move freely within a protected area. The aim of the Reserve Network Design Problem is to choose a network of contiguous sites which maximises some conservation objective subject to various constraints. The problem has been solved using both heuristic and exact methods. Heuristic methods can handle much larger problems than exact methods but cannot guarantee an optimal solution. Improvements in both computer power and optimisation algorithms have increased the attractiveness of exact methods. The aim of this work is to formulate an improved algorithm for solving the Reserve Network Design Problem.

Based on the concept of the transshipment problem a mixed integer programming model is formulated that achieves contiguity of the selected sites. The model is simpler in concept and to implement than previous exact models and does not require any assumptions about the regular shape of candidate sites. The method easily handles the case where more than one reserve system is required. We illustrate this with an example obtaining the trade-off between the number of contiguous areas and utility. We also illustrate that the important property of compactness can be achieved while maintaining contiguity of selected sites.

1. Introduction

The threat to species and their ecosystems due to loss of habitat from anthropogenic activities is well recognised. A common strategy to conserve biodiversity in the landscape is to purchase land where key habitats, species and ecosystems can be conserved (Snyder et al., 2004). To this end large investments are being made by European and United States governments to build conservation networks (European Commission, 2006; Farm Service Agency, 2006; Ribaudo et al., 2001; Hajkowicz et al., 2008). In Australia, the federal government has committed A$5.8 billion to the National Heritage Trust program over the period 1996–2013 (Australian Government, 2007).

The "Reserve Site Selection Problem" (RSSP) has been addressed in numerous optimisation studies since the early 1980s (Kirkpatrick, 1983; Margules et al., 1988; Haight et al., 2000; Ruliffson et al., 2003; Moilanen, 2005a,b; Newbold and Siikamaki, 2009). These studies involve selecting sites that minimise costs while meeting conservation constraints or that maximise some conservation objective subject to budget constraints (Williams et al., 2005). Pockets of isolated sites may arise in solutions to the RSSP. Often more desirable is a solution comprising a network of connected sites. The problem of choosing a contiguous set of sites which optimises an objective such as biodiversity is known as the "Reserve Network Design Problem" (RNDP) and is the focus of attention in this paper. Various objectives have been used in the RSSP and the RNDP such as species richness, rarity, diversity, shape and other attributes of a site for which protection is desired (European Commission, 2006; Pressey et al., 1993; Memtsas, 2003). Dissanayake et al. (2011) addressed a problem with the objectives of simultaneously choosing land for conservation purposes and military training.

The RNDP is NP-hard meaning that the computational effort increases exponentially with site numbers, and hence mainly heuristic methods are used especially for large scale problems (Kirkpatrick, 1983; Margules et al., 1988; Possingham et al., 1993; Williams et al., 1996; Pressey et al., 1997; Nalle et al., 2002; Cerdeira et al., 2005). For example, Pressey et al. (1993) used a greedy algorithm selecting sites in the order of greatest species' richness. Kershaw et al. (1994) used a similar approach prioritizing sites with a high existence value of rare or endangered species with the aim of finding the minimum number of sites to represent all species at least once. Although heuristic methods are effective for large scale problems there is no guarantee that they achieve an optimal solution. Moreover, increases in computational power and improvements in optimisation algorithms will see an increasing role for exact methods in solving NP-hard problems. The remainder of this paper deals with exact methods.

* Corresponding author. Tel.: +61 411 481 387.
E-mail address: jnahid@hotmail.com (N. Jafari).

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A Linear Integer Programming Problem (LIP) arises when the RSSP is viewed as a set covering problem where the objective is to find the minimum number of reserve sites that contain all species at least once. Similarly, an LIP model is obtained for the maximal coverage formulation where a given number of sites are to be selected with the objective of maximising the number of species represented (Camm et al., 1996; Church et al., 1996; ReVelle et al., 2002; Rodrigues et al., 2000). These formulations did not rigorously address the RNDP where contiguity of the selected sites is also desired. Using graph theoretical methods Williams (2002) formulated the first general, practical LIP method for land acquisition that enforced contiguity. The method required the specification of the number of sites to be selected. Shirabe (2005) described this work as setting "a standard for evaluating other exact contiguity models that may follow".

Others have also used graph theory and network optimisation (Önal and Briers, 2005, 2006; Önal and Wang, 2008; Conrad et al., 2012) to solve the RNDP. Where resources were sufficient Önal and Wang (2008) considered minimising the sum of gaps between neighbouring sites to encourage a fully connected reserve. Conrad et al. (2012) proposed a hybrid approach for finding corridors connecting multiple protected areas together. In this case contiguity of selected sites was enforced. They employ graph theoretic techniques to trim as much as 40% off the branches involved in the usual solution procedure for an MIP model.

In this paper we develop a novel mixed integer programming (MIP) formulation of the RNDP. The formulation is much simpler in both concept and implementation than other mathematical programming formulations such as those by Williams (2002) and Önal and Wang (2008). Using the concept of a transshipment problem the method is flow-based. Shirabe (2005) also used a flow-based method. This method required preselecting a site for each reserve system required in the landscape to act as a sink. The method ensures contiguity of the sites selected. In contrast to the method of Shirabe (2005) our method does not require any site to be preselected. It also deals with the flow of capital explicitly. The method works with both grids and irregularly shaped candidate sites. The method can be used to deal with the archetypal problems known as the Species Set Covering Problem (SSCP) (Moore et al., 2003; Cerdeira and Pinto, 2005) and the Maximal Species Covering Problem (MSCP) (Church et al., 1996; Polasky et al., 2001; Rosing et al., 2002). In addition to contiguity, compactness is often an important property of a solution. The method can easily accommodate this requirement with the addition of a few extra terms similar to those reported in the literature (Nalle et al., 2002; Briers, 2002; Önal and Briers, 2002, 2003; Fischer and Church, 2003; Toth and McDill, 2008; Haight and Snyder, 2009).

Cycling occurs when a sequence of selected nodes returns to a node that has already been selected. It can result in disjoint clusters of selected nodes. More details can be found in (Önal and Wang, 2008). Önal and Wang (2008) and Williams (2002) introduced additional constraints to avoid this problem. Our method ensures contiguity without incurring the problem of cycling as every node can only be visited at most once.

Being an exact method the proposed MIP model guarantees a global optimum. The model is also applicable for cases where full connectivity is not feasible or more than one fully connected reserve system is desirable in a region. In fact the model allows for the easy investigation of the trade-off between one or more fully connected reserves to be determined. This is illustrated in Section 3. First the algorithm is described in the following section. In later sections we show how the basic model can be modified to deal with two archetypal problems. Further, we make some modifications to deal with the important property of compactness and illustrate its use. We also report on some experimental results concerning the size of problem that can be solved with our method.

2. The Method

2.1. Description

Consider a region comprising a mosaic of sites, each with its own attributes such as price and some measure of utility. The region can be represented by a network where each site is a node. An arc is defined between two nodes for every case where sites have a common boundary.

2.2. Contiguity

Our aim is to find a set of nodes that are connected and maximise the total utility of the connected nodes given a limited budget. Utility can represent various attributes that are considered desirable such as species richness, habitat suitability for threatened species, or a weighted combination of such attributes. We formulate this problem using the concept of a transshipment problem. To our network we add a supply node containing the total capital available in the budget. Each node is regarded as a transshipment node and has a demand equal to the price of land that the node represents. This demand can be met by 'shipping' capital to the node directly from the supply node or from another transshipment node through which sufficient capital has flowed. A node whose demand has been met represents a site that has been purchased. Each purchase adds to the total utility of the reserve network. Capital cannot flow though a transshipment node without the demand at that node being met first. Capital can only flow along arcs, in other words from a transshipment node to one or more of its neighbouring nodes. In this way connectivity of the reserve is achieved. The objective is to direct the flow of capital to the nodes to maximise the aggregate utility of the nodes whose demands have been met. The concepts are illustrated in Fig. 1.

2.3. Formulation

The proposed model is a mixed integer program that selects a subset of sites which are fully connected to maximise the utility given a limited budget.

$$Max \sum_{i=1}^{N}\sum_{j\in N_i} y_{ji} * u_i \quad (1)$$

subject to

$$\sum_{i=1}^{N} x_{0i} \leqslant B \quad (2)$$

$$\sum_{j\in N_i} x_{ji} - \sum_{j\in N_i-\{0\}} x_{ij} = c_i * \sum_{j\in N_i} y_{ji}, \quad \forall i = 1,\ldots,N \quad (3)$$

$$\sum_{j\in N_i} y_{ji} \leqslant 1, \quad \forall i = 1,\ldots,N \quad (4)$$

$$y_{ij} \leqslant x_{ij}, \quad \forall i = 1,\ldots,N, j\in N_i \quad (5)$$

$$x_{ij} \leqslant B * y_{ij}, \quad \forall i = 1,\ldots,N, j\in N_i \quad (6)$$

$$\sum_{i=1}^{N} y_{0i} = 1 \quad (7)$$

$$y_{ij} \in \{0,1\}, x_{ij} \geqslant 0, \quad (8)$$

where x_{0i} is a variable that indicates the flow of capital from the supply node (node 0) to node i; x_{ij} is a variable that indicates the flow of capital from node i to node j; $y_{ij}(i,j = 1,\ldots,N)$ is a binary variable indicating whether or not capital flows along the arc i, j, that is;

$$y_{i,j} = \begin{cases} 1, & \text{if } x_{ij} > 0 \\ 0, & \text{otherwise} \end{cases} \quad (9)$$