An Interactive Strategy for Solving Multi-Criteria Decision Making of Sustainable Land Revitalization Planning Problem

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Abstract. Land revitalization refers to comprehensive renovation of farmland, waterways, roads, forest or villages to improve the quality of plantation, raise the productivity of the plantation area and improve agricultural production conditions and the environment. The objective of sustainable land revitalization planning is to facilitate environmentally, socially, and economically viable land use. Therefore it is reasonable to use participatory approach to fulfill the plan. This paper addresses a multicriteria decision aid to model such planning problem, then we develop an interactive approach for solving the problem.

Keywords: Multi-criteria decision analysis, Modeling, Land revitalization, Interactive approach

1. Introduction

Land is used to meet a multiplicity and variety of human needs and to serve numerous, diverse purposes. Land revitalization is the sustainable redevelopment of abandoned a large piece of land. The main objective of the program is to encourage communities and land owners to reuse and redevelop land that was previously abandoned and turns it into something useful, such as, public parks, restored wetlands, and new businesses. Therefore revitalizing has a rich meaning to a community as to make it safer, greener, and offers more jobs to its residents.

In the revitalization planning program, we examine the effects of uncertainty and irreversibility in valuing and timing conversion and development projects involving land areas or natural resources. This topic has been addressed first by [2, 15], who treat the complete conversion problem as an optimal stopping problem, while the gradual conversion problem was first introduced by [6]. Our analysis is focused on a more general problem that is finding an optimal land/resources portfolio composition through time, in the presence of future market uncertainty. In fact, it is often more realistic to assume that an optimal land management program will involve a gradual sequence of conversion decisions through time, evolving as each land allocation/resource value becomes known more accurately.

In this paper we formulate a scenario-based multi-stage stochastic programming model, which takes into account the uncertainty related to the market value of revenues accruing from the land in different states. As most of the real options literature assumes, whenever the riskiness of a project is diversifiable, as it is in the case of market uncertainty, it is possible to compute the value of the project applying the “risk-neutral” probability distribution and using the risk-free interest rate. In order to take into account the non-constant incremental benefits accruing from different land allocations, we consider piece-wise
linear land-use value functions. In fact, in realistic settings, where quantity-dependence is admitted, the incremental value of developed land is contingent on the size of the conversion, see [26].

The second issue investigated is environmental uncertainty. In fact, when we allow for the option of converting an area into a natural park, or, more generally, we include in the model preservation investments, we have to deal, not only with market uncertainty, but also with the more complex and domain specific uncertainty about environmental quality, see [7, 4]. The latter issue is a consequence of the fact that policies are usually concerned with long time horizon decisions, their effects on the environment may be partly unknown and also that environmental processes are stochastic. For example, we typically lack information on the amount of ultimately recoverable resources, characteristics of future technologies and their arrival dates, tastes of people in the future, and so on. Historical data series on fluctuations of natural land value shows discontinuities and frequently a greater volatility when compared to other commercial development opportunities. This often implies that markets are incomplete, thence the riskiness of the environmental investment cannot be hedged by a replicating portfolio and the “risk-neutral” approach cannot be applied.

Nevertheless, option pricing can be profitably integrated to decision analysis methods in order to deal with this domain specific risk. In particular, option pricing techniques can be used to simplify decision analysis when some risks can be hedged by trading and, conversely, decision analysis techniques can be used to extend option pricing techniques to problems with incomplete securities markets, as shown in [25]. Supposing that the decision maker can either choose to sharpen knowledge about the initial value accruing from the preserved land, or take decisions without any further inquiry, we model the gradual conversion problem using a decision tree framework, in [3].

2. Problem formulation
2.1. Model Notation
This model is developed using a grid of cells which represent portion of land

- \( j = 1, 2, ..., n; \) where \( n \) is the total number of cells (portion of land) in the area
- \( l, m = 1, 2, ..., k \) types of land uses
- \( u \) = undeveloped land use type or status quo (SQ)
- \( D_l \) = set of cells that already have land use \( l \)
- \( D_M \) = set of cells that already have land use \( M \)
- \( U \) = set of cells of SQ land
- \( e_j \) = existing land use of cell \( j \)
- \( k_l \) = number of cells that initially have land use \( l, l = 1, 2, ..., k \)
- \( v_l \) = estimated demand for land use \( l \)
- \( X_{jluM}(t) = \begin{cases} 1 & \text{if SQ land at location } j \text{ is converted to } M \text{ at time } t \\ 0 & \text{otherwise} \end{cases} \)
- \( X_{jlejM}(t) = \begin{cases} 1 & \text{if land use } e_j \text{ at location } j \text{ is converted to } M \text{ at time } t; \ M \neq e_j \\ 0 & \text{otherwise} \end{cases} \)
- \( X_{jlmM}(t) = \begin{cases} 1 & \text{if land use } l \text{ at location } j \text{ is converted to } M \text{ at time } t; \ M \neq l \\ 0 & \text{otherwise} \end{cases} \)
- \( W_{juM}(t) \in [0,1] \) portion of SQ land at location \( j \) is converted to \( M \) at time \( t \)
- \( W_{jelM}(t) \in [0,1] \) portion of land use \( e_j \) at location \( j \) is converted to \( M \) at time \( t \)
- \( W_{jlmM}(t) \in [0,1] \) portion of land use \( l \) at location \( j \) is converted to \( M \) at time \( t \)
- \( U(t) \in [0,1] \) the portion of undeveloped land at time \( t \)
- \( D(t) \in [0,1] \) the portion of land use \( l \) at time \( t \)
- \( D_{M}(t) \in [0,1] \) the portion of land use \( M \) at time \( t \)
We define the benefits and costs accruing from alternative land allocation:

$\pi(t, U(t))$ the discounted values of revenue arising at time $t$ for the portion of undeveloped land $K(t, D_l(t))$ the discounted values of revenue arising at time $t$ for the portion of land use $l$

$\nu(t, D_M(t))$ the discounted values of revenue arising at time $t$ for the portion land use $M$

$\alpha(t)$ represents the discounted values of variable cost deriving from conversion SQ land to $M$ at location $j$

$\beta(t)$ represents the discounted values of variable cost deriving from conversion of land use $e_j$ to $M$ at location $j$

$\gamma(t)$ represents the discounted values of variable cost deriving from conversion of land use $l$ to $M$ at location $j$

$I_\alpha(t)$ the initial sunk costs necessary to start the conversion of the area SQ to $M$ at location $j$

$I_\beta(t)$ the initial sunk costs necessary to start the conversion of the area land use $e_j$ to $M$ at location $j$

$I_\gamma(t)$ the initial sunk costs necessary to start the conversion of the land use $l$ to $M$ at location $j$

The decision maker objective is to maximize the Net Present Value (NPV) deriving from the managed area, considered both revenues and variable and fixed conversion costs:

$$\max \sum_{t=1}^{T} \left[ \pi(t, u(t)) u(t) + k(t, D_l(t)) D_l(t) + \nu(t, D_M(t)) D_M(t) + \alpha(t) w_{jum}(t) + \beta(t) w_{jejm}(t) + \gamma(t) w_{jlmt}(t) \right] +$$

$$- \sum_{t=1}^{T} \left[ I_\alpha(t) x_{jum}(t) + I_\beta(t) x_{jejm}(t) + I_\gamma(t) x_{jlmt}(t) \right]$$

To include fixed initial investment costs in the model, we have introduced three binary variables each assuming the value one (zero) when the correspondent conversion activity has (has not) been undertaken. $x_{jum}(t) \in \{0, 1\}$, $x_{jum}(t) = 1$ if conversion from SQ into $M$ starts at time $t$; $x_{jum}(t) = 0$, otherwise; analogously we introduce $x_{jejm}(t) \in \{0, 1\}$, relating to conversion from $M$ into $l$ and $x_{jlmt}(t) \in \{0, 1\}$, relating to conversion from SQ into $l$.

The maximization problem is constrained to investment constraints, formalizing the presence of fixed costs when conversion starts, for $i = \alpha, \beta, \gamma$, with $t \in \{1, \ldots, T\}$:

$$w_i(t) \leq \sum_{t'=1}^{T} x_{j}(t')$$

$$\sum_{t=1}^{T} x_{j}(t) \leq 1$$

3. The Stochastic Programming Model

When uncertainty concerning benefit flows is included in the model, the decision made at each period should take into account all future uncertainties and future decisions. For the sake of simplicity we denote by $\xi$ the random vector defined as $\xi = (\xi_\pi, \xi_\nu, \xi_\nu)$. 
We can now set out the stochastic linear programming problem as follows:

\[
\begin{align*}
\max & \quad E_\xi \sum_{i=1}^{T} [\pi(t, u(t); \xi)u(t, \xi) + k(t, D_i(t); \xi)D_i(t, \xi) + v(t, z(t); \xi)D_M(t, \xi) + \\
& - E_\xi \sum_{i=1}^{T} (\alpha(t)w_{jum}(t, \xi) + \beta(t)w_{jejm}(t, \xi) + \gamma(t)w_{jlm}(t, \xi)) + \\
& - E_\xi \sum_{i=1}^{T} [I_\alpha(t)x_{jum}(t, \xi) + I_\beta(t)x_{jejm}(t, \xi) + I_\gamma(t)x_{jlm}(t, \xi)]
\end{align*}
\]

where \( E_\xi \) represents the expectation operator relative to the random vector \( \xi \). Again the maximization problem is subject to the following constraints:

1) Initial conditions, for \( t = 0 \):

\[
u(t, \xi) = 1 \quad \text{and} \quad D_j(t, \xi) = D_0(t, \xi) = w_{jum}(t, \xi) = w_{jejm}(t, \xi) = w_{jlm}(t, \xi) = 0.
\]

2) Investment constraint, for \( i = \alpha, \beta, \gamma \), and \( t \in \{1, \ldots, T\} \),

\[
w_i(t, \xi) \leq \sum_{i=1}^{T} x_i(t', \xi), \quad a.s.
\]

3) Development constraints, for \( t \in \{1, \ldots, T\} \),

\[
u(t, \xi) = u(t-1, \xi) - w_{jum}(t, \xi) - w_{jejm}(t, \xi),
\]

\[
D(t, \xi) = D_i(t-1, \xi) + w_{jum}(t, \xi) - w_{jejm}(t, \xi),
\]

\[
D_M(t, \xi) = D_M(t-1, \xi) + w_{jum}(t, \xi) + w_{jejm}(t, \xi),
\]

\[
u_0(t, \xi) \leq v(t-1, \xi), \quad a.s.
\]

4) Conservation constraints, for \( t \in \{1, \ldots, T\} \),

\[
u(t, \xi) + D(t, \xi) + D_M(t, \xi) = 1.
\]

5) Information constraints, i.e., for \( t \in \{1, \ldots, T\} \), \( u_i \) is the \( \mathcal{F}_t \)-measurable, where \( \mathcal{F}_t \) is the \( \sigma\)-field generated by the observations, i.e.,

\[
\mathcal{F}_t = \sigma\{\xi_r | r \leq t\},
\]

where \( \xi_t \) represents the realization of the random vector at time \( t \), for \( i = \alpha, \beta, \gamma \).

An important prerequisite, in order to solve the maximization problem, is the discretization of the stochastic processes representing the evolution of the random data, \( \xi \). The aggregation of the discrete processes can be represented by a scenario (event) tree that defines the possible sequences of realizations over the whole planning horizon. Note that nodes in the event tree are associated with decision points while arcs represent realizations of random variables. In particular, the root is associated with the first stage decision variables while leaves are related to all the possible last stage ones. If we denote with \( N_t \) the set of nodes at the \( t \)-th level, then each node \( n \in N_t \) represents a particular realization sequence \( \{\xi_t\}^t = 1 \) of the data process and it can be thought as a particular state of the system at a given time. A probability \( p_n \) can be associated with each node \( n \) at level \( t \) such that \( p_n = p\{\xi_t \xi_{t-1}, \ldots, \xi_1\} \).

4. The Deterministic Equivalent Model

Given a set \( Z \) of cancelled route, a route \( (v_1, v_2, v_3, \ldots, v_l) \) is said to avoid \( E \) if \( (v_i, v_i+1, \ldots, v_j) \notin E \) for all \( i, j \) such that \( 1 \leq i < j \leq l \). A route \( Q \) from \( s \) to \( t \) is called a shortest \( E \)-avoiding route if the length of \( Q \) is the shortest among all \( E \)-avoiding route from \( s \) to \( t \). We will use the term “exception avoiding” instead of “\( X \)-avoiding” when \( E \) is equal to \( Z \), the set of all cancelled paths in \( G \).
After the discretization process using a scenario tree approach we can write the deterministic equivalent model as follows.

\[
\max \sum_{s \in S} p(s) \sum_{t=0}^{T} [\pi(t, s)u(t, s)] + \\
+ \sum_{s \in S} p(s) \sum_{m=1}^{M} [K(m, t, s)dD_{m}(m, t, s)] + \\
+ \sum_{s \in S} p(s) \sum_{m=1}^{M} m[V(m, t, s)dD_{m}(m, t, s)] + \\
- \sum_{s \in S} p(s) [\alpha(t)w_{jm}(t, s) + \beta(t)w_{jejm}(t, s) + \gamma(t)w_{jm}(t, s)] + \\
- \sum_{s \in S} p(s) [I_{a}(t)x_{jm}(t, s) + I_{P}(t)x_{jejm}(t, s) + I_{p}(t)x_{jm}(t, s)]
\]

The objective function is constrained to:

1) Initial conditions, for each \( s \in S \) and for \( t = 0 \),
\[ u(t, x) = 1 \text{ and } D(t, s) = D_{0}(t, s) = w_{jm}(t, s) = w_{jejm}(t, s) = 0. \] (10)

2) Investment constraints, for each \( s \in S \), for \( i = \alpha, \beta, \gamma \), and \( t \in \{1, \ldots, T\} \),
\[ w_{i}(t, s) \leq \sum_{t' \leq t} x_{i}(t', s), \]
\[ \sum_{t} x_{i}(t, s) \leq 1. \] (11)

3) Development constraints, for each \( s \in S \) and \( t \in \{1, \ldots, T\} \),
\[ u(t, s) = u(t - 1, s) - w_{jm}(t, s) - w_{jejm}(t, s), \]
\[ D(t, s) = D(t - 1, s) + w_{jm}(t, s) - w_{jejm}(t, s), \]
\[ D(t, s) = D_{0}(t - 1, s) + w_{jm}(t, s) - w_{jm}(t, s), \]
\[ w_{jm}(t, s) \leq D(t - 1, s). \] (12)

4) Conservation constraint, for any \( s \in S \) and for \( t \in \{1, \ldots, T\} \),
\[ D_{M}(t, s) + D(t, s) + D_{0}(t, s) = 1. \] (13)

5) Non-anticipativity constraints, defined in such a way that the dependencies implied by the scenario tree are satisfied. Defining \( B_{n} \) the bundle of scenarios passing through node \( n \), then
\[ u(t, s_{i}) = u(t, s_{j}), i \neq j, s_{i}, s_{j} \in B_{n}, \text{ with } n \in N, t = 1, \ldots, T - 1, \]
\[ D(t, s_{i}) = D(t, s_{j}), i \neq j, s_{i}, s_{j} \in B_{n}, \text{ with } n \in N, t = 1, \ldots, T - 1, \]
\[ D_{0}(t, s_{i}) = D_{0}(t, s_{j}), i \neq j, s_{i}, s_{j} \in B_{n}, \text{ with } n \in N, t = 1, \ldots, T - 1. \] (14)

6) Piece-wise linear value of land constraints, defined for each \( s \in S \), with \( t \in \{0, \ldots, T\} \).

7) Constraints to ensure that we can allocate maximally one land use to each cell \( j \)
\[ \sum_{m \in j} x_{jm}(t) \leq 1, \forall j \in D, t = 1, \ldots, T \]
\[ \sum_{m} x_{jm}(t) \leq 1, \forall j \in U, t = 1, \ldots, T \] (15)

8) Constraint that guarantees the demand for land use \( l \) is satisfied
\[ t_{l} - \sum_{l \in D_{0}} \sum_{m \in l} x_{jm}(t) + \sum_{j \in (D_{0}D_{l})} x_{jejm} + \sum_{j \in U} x_{jul} \geq v_{l}; \forall l \] (16)
5. Conclusions

This paper presents a model to plan land revitalization in order to redevelop the abandoned a large piece of land. We formulate a scenario-based multi-stage stochastic programming model, which takes into account the uncertainty related to the market value of revenues accruing from the land in different states.

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