Environmental Modelling & Software 71 (2015) 126–137

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Spatial forest resource planning using a cultural algorithm with problem-specific information☆

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A R T I C L E I N F O

Article history:
Received 6 October 2014
Received in revised form
9 April 2015
Accepted 8 June 2015
Available online 24 June 2015

Keywords:
Forest planning
Harvest scheduling
Landscape design
Evolutionary algorithm
Cultural algorithm

A B S T R A C T

A cultural algorithm (CA) is proposed for the spatial forest resource planning problem that aims at maximizing the total timber volume harvested over a harvest planning schedule, subject to constraints of minimum harvest age, minimum adjacency green-up age, and approximately even volume flow for each period of the schedule. To increase the solution-search ability, the CA extracts problem-specific information during the evolutionary solution search to update the belief space of each generation, which has cultural influences and guidance on the next generation. The key design of the proposed CA is to propose the cultural and evolutionary operators specifically for the problem. This work is of high value as a comprehensive experimental analysis shows that the proposed CA rooted from evolutionary algorithm (EA) obtains 0.44%–1.13% better fitness and performs more stably than the previous best-known simulated annealing (SA) approach, which was shown to perform better than the EA previously.

1. Introduction

Forests play multiple roles—production, protection as well as recreation, and hence forest resource planning has been attracting a lot of attention from not only forest owners but also society. Forest resource planning becomes increasingly complicated as multiple economic, environmental, and social criteria are taken into account, e.g., impacts of forest planning operations on water pollution, erosion, landscape aesthetics, and biodiversity (Diaz-Balteiro and Romero, 2007). Among those criteria, spatial concern in forest resource planning is of importance as it maintains a number of environmental and ecological conditions, e.g., maintenance of biodiversity, limited sediment loading in streams, limited disruption of habitats in an area, limited impact on a viewshed, supply of open forage areas for certain animals, and so on (Church et al., 1998; Baskent, 2001; Kurttila, 2001; Lehtomaki and Moilanen, 2013). For instance, clearcutting activities of one forest harvest unit may expose neighboring forest stands to wind damage, bark injuries, drainage problems, and site class deterioration (Malchow-Moller et al., 2004). Furthermore, various types of damages or spatially uncontrolled management implementations can result in decreased wood quality, habitat disruption, water pollution, increased sediment quantities, and so on. Based upon the above reasons, it is common that spatial constraints on minimum adjacency green-up age are imposed upon harvesting activities on adjacent forest stands or harvest units.

The focus of this work is on a spatial forest resource planning problem which aims at maximizing the timber volume harvested over a harvest planning schedule with consideration of the minimum harvest age constraint, the minimum adjacency green-up age constraint, as well as the constraint of approximately even volume flow for each period of the schedule. From the previous literature, several solutions have been used for solving different types of spatial forest resource planning problems, among which exact solutions include Metropolis algorithm (Van Deusen, 1999), mixed integer programming (Bare and Eldon, 1969; Bevers and Hof, 1999; McDill and Rebain, 2003), and dynamic programming (Hoganson and Borges, 1998); while metaheuristic approaches include penalty function with simulated annealing (Lockwood and Moore, 1993), tabu search (Murray and Church, 1999), and evolutionary algorithm (Liu et al., 2006), among others. Some articles focused on conducting comprehensive experimental comparison on several heuristics, e.g., see (Liu et al., 2006; Pukkala and Kurttila, 2005).

☆ A preliminary version of this work was presented at 2014 IEEE Congress on Evolutionary Computation (CEC 2014), Beijing, China, July 6–11, 2014.

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http://dx.doi.org/10.1016/j.envsoft.2015.06.002
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This work proposes a cultural algorithm approach to the above spatial forest resource planning problem. The cultural algorithm (CA) (Reynolds, 1994) is an evolutionary algorithm (Fogel, 1995; Yu and Gen, 2010) which improves performance of evolutionary search by extracting domain knowledge of the problem of concern during the search process. In addition to the conventional evolutionary settings that act on a population of individuals (candidate solutions) and intend to iteratively improve fitness (probably in terms of the objective function of the problem of concern) of each individual, it maintains a belief space consisting of a half of individuals with better fitness values from the current population, as well as a leader to guide the whole population. During the search process, the belief space and the leader are updated by incorporation of the extracted problem-specific knowledge, and they influence each individual in the population to obtain better solutions. As a result, this work investigates how to design a CA specifically for the spatial forest resource planning problem with the above concerns. For performance evaluation, the proposed algorithm is experimentally compared with the previous best-known simulated annealing approach to the same problem in (Liu et al., 2006).

In the past, optimization problems were usually handled by gradient search methods, which require substantial gradient information. However, lots of practical optimization problems are much complex and may have multimodal solution space, so that the gradient search may be unstable and difficult (Lee and Geem, 2005). Hence, most recent works focused on developing metaheuristic algorithms for optimization problems. This work proposes a metaheuristic algorithm based on CA for the problem of concern.

The rest of this work is organized as follows. Section 2 gives the preliminaries of this work, which include the introduction to the basic settings of the problem of concern, the previous approaches to this problem, and the cultural algorithm. Section 3 gives the proposed approach based upon the cultural algorithm, while Section 4 gives the implementation of the proposed approach and the experimental results under a variety of parameters. Section 5 concludes this work.

2. Preliminaries

This section first gives basic settings of the spatial forest resource planning problem of concern, and then introduces the two previous approaches proposed in (Liu et al., 2006). Finally, the basic idea of cultural algorithm is introduced.

2.1. Problem setting

The spatial forest resource planning problem of concern in this work is the same with (Liu et al., 2006), which is detailed as follows. Consider a forest land that consists of a number of smaller polygonal forest lands, called *polygons*, in which any two neighboring polygons are said to have an adjacency relation. Generally, forests in the same polygon land could be at different ages and of different species, so it is hard to precisely estimate the harvested timber volume. Additionally, harvests could be made at any time point, because time is continuous. Hence, for simplify the problem, it is supposed that forests in each polygon are at an equal age and of the same species, and harvests occur only at the beginning of a planning time period.

Consider to serve as the role of the forest planner who aims at planning a harvest schedule of the forest land that is divided into a number of time periods. The problem of concern is to select a number of forest polygons to be harvested at the beginning of each period to achieve the following objective:

Maximize the total timber volume of all forest polygons harvested during all periods, subject to the following three constraints:

- Minimum harvest age constraint: At the beginning of each period, only the polygons at age greater than a minimum age threshold can be harvested.
- Minimum adjacency green-up age constraint: At the beginning of each period, a forest polygon can be harvested only when the age of each of its adjacent forest polygons is no less than the predetermined minimum green-up age.
- Constraint of approximately even volume flow for each period of the harvest schedule: To balance the harvest volume of each period, this constraint enforces the timber volume for each period to be harvested as even as possible.

Note that the adjacency rule in the above second constraint is crucial because harvest should be dispersed for hydrological and wildlife reasons about concentrated harvests associated with progressive clearcutting. The green-up age is the age that a regenerated stand must reach before an adjacent unit can be harvested.

Since forest polygons are harvested only at the beginning of each period, the minimum adjacency green-up age constraint is always satisfied if the length of each period is assumed to be greater than the minimum adjacency green-up age. In more detail, the minimum adjacency green-up age constraint allows to harvest a forest polygon only when the age of each of its adjacent forest polygons is no less than the minimum green-up age, in which period length and the minimum adjacency green-up age are predetermined. If the length of each period is set to be greater than the minimum adjacency green-up age, the age of the forests harvested only at the beginning of each period must be greater than the minimum adjacency green-up age, and hence, the minimum adjacency green-up age constraint is satisfied.

To compare performance of this work with (Liu et al., 2006), this work continues using the setting in (Liu et al., 2006), in which the minimum harvest age is 90 years, and the length of each period is 20 years, which are always greater than the minimum adjacency green-up age − 15 years. With this setting, it suffices to consider the adjacency relationship of polygons in solving the problem, i.e., it only needs to consider that any two adjacent polygons cannot be harvested in the same period, with no need to check their age difference.

2.2. Evolutionary algorithm for spatial forest planning

The *evolutionary algorithm* (EA) is a stochastic global search method, among which genetic algorithm (GA) is the most popular type of EA, and has been proved to be successful for a variety of environmental optimization problems, e.g., water distribution system (Bi et al., 2015; Zheng et al., 2015; Gupta et al., 1999), forecasting value of agricultural imports (Lee and Liu, 2014), estimation of soil organic and mineral fraction densities (Crowe et al., 2006), among others. A survey on the applications of EA in water resources can be found in (Maier et al., 2014). EA allows the solution representation to be a sequence of base-10 numbers, tables or other data structures. It works with a population of individuals (candidate solutions) and tries to optimize the answer by using three basic evolutionary principles, including *selection*, *crossover* (also called recombination), and *mutation*. The pseudo code of EA for the forest resource planning problem of concern in (Liu et al., 2006) is stated in Algorithm 1, in which the iteration number N is used to count the total iterations of the main loop (see Lines 3, 9, and 10).

The key steps of Algorithm 1 are explained as follows.