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Innovative Applications of O.R.

A cutting plane method for solving harvest scheduling models with area restrictions

Nóra Könnyű, Sándor F. Tóth *

School of Environmental and Forest Sciences, University of Washington, Box 352100, Seattle, WA 98195, USA

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ABSTRACT

We describe a cutting plane algorithm for an integer programming problem that arises in forest harvest scheduling. Spatial harvest scheduling models optimize the binary decisions of cutting or not cutting forest management units in different time period subject to logistical, economic and environmental restrictions. One of the most common constraints requires that the contiguous size of harvest openings (i.e., clear-cuts) cannot exceed an area threshold in any given time period or over a set of periods called green-up. These so-called adjacency or green-up constraints make the harvest scheduling problem combinatorial in nature and very hard to solve. Our proposed cutting plane algorithm starts with a model without area restrictions and adds constraints only if a violation occurs during optimization. Since violations are less likely if the threshold area is large, the number of constraints is kept to a minimum. The utility of the approach is illustrated by an application, where the landowner needs to assess the cost of forest certification that involves clear-cut size restrictions stricter than what is required by law. We run empirical tests and find that the new method performs best when existing models fail: when the number of units is high or the allowable clear-cut size is large relative to average unit size. Since this scenario is the norm rather than the exception in forestry, we suggest that timber industries would greatly benefit from the method. In conclusion, we describe a series of potential applications beyond forestry.

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1. Introduction

We propose a cutting plane algorithm to optimize area-based forest harvest scheduling. Harvest scheduling models, that are typically cast as integer programs, optimize the spatiotemporal layout of harvests subject to a variety of logistical, economic and environmental constraints. Area-based models ensure that the contiguous size of harvest openings (i.e., clear-cuts) cannot exceed a maximum threshold in any given time period or over a set of periods called green-up. Area-based harvest scheduling problems are combinatorial problems that are often very hard to solve to optimality. The proposed cutting plane algorithm starts with a model without area restrictions and adds constraints only if a violation occurs during optimization. Before providing a formal definition of the algorithm, we give a brief background and literature review on harvest scheduling models.

The National Forest Management Act of 1976 was the first piece of legislation in the United States that imposed restrictions on the size of clear-cuts. The Act responded to public criticism, which emerged in the 1960s, that large clear-cuts compromised wildlife habitat and other forest ecosystem functions. Many states followed suit and established clear-cut size regulations on both private and state forestlands [3]. Forest certification standards such as those administered by the Forest Stewardship Council (FSC) or the Sustainable Forestry Initiative (SFI) also dictate various limits on harvest opening sizes [16]. The compliance of forest managers who enroll in an FSC or SFI program, is ensured by periodic third-party audits.

The intention behind the policy of restricting harvest opening sizes was to reduce the spatial and temporal concentration of harvest activities across the landscape. A possible side effect of this policy, however, a heterogeneous, patchy forest landscape, has been shown to have both positive and negative ecological consequences [15]. A forest with a spatially heterogeneous age-class distribution is more resilient against the spread of fire, but the increased amount of edge will increase the likelihood of windthrow and compromise interior old forest habitat. Clear-cut size restrictions may also reduce timber revenues.

Computing the tradeoffs between timber revenues and landscape metrics is useful for policy makers, for the designers of forest certification standards and for forest landowners/managers who are interested in certification. However, such tradeoff analyses may be prohibitively expensive. The larger the opening limit relative to the average size of the harvest units, the harder it is to formulate and solve these models [18]. We give a brief overview of prior work on spatial harvest scheduling and discuss a real-life example that illustrates the computational issues that can arise.

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* Corresponding author. Tel.: +1 206 616 2738.
E-mail addresses: norakonnyu@gmail.com (N. Könnyű), toths@uw.edu (S.F. Tóth).

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1.1. Area-based harvest scheduling in forestry

Harvest scheduling models seek to maximize timber revenues or other outputs subject to environmental, logistical or budgetary constraints by assigning harvest decisions to forest management units (contiguous groups of trees that share similar characteristics such as species or average height) over a planning horizon. "Environmental" or sustainability constraints might include ending timber volume (inventory) requirements, a balanced flow of timber revenues, or maximum harvest opening size restrictions. Harvest scheduling models that incorporate maximum harvest opening size constraints are called Unit- or Area Restriction Models [30, a.k.a., URM vs. ARM], depending on whether or not the combined area of every pair of adjacent units exceeds the allowable area threshold. If it does, the problem is a URM that prevents adjacent forest stands from being harvested simultaneously or within a pre-specified timeframe called the green-up or exclusion period. Otherwise, the problem is an instance of the ARM.

The core of the URM, which was first formulated as a mixed integer program (MIP) by [20], and subsequently by [28,31,32,44] is an instance of the Node Packing Problem, a.k.a. the Vertex Packing or the Maximal Weight Stable Set Problem in integer programming. The ARM is a more general model; it allows groups of contiguous management units to be harvested concurrently as long as their combined area is less than the maximum harvest opening size. The ARM typically arises when the maximum harvest opening size is large relative to the size of the units. Since the ARM is a generalization of URM, it can be viewed as a Stable Set problem, where the requirement on the independence of the nodes is relaxed subject to a pre-specified threshold. While this threshold is defined as area in forest planning, it does not have to be – giving rise to potential applications beyond forestry. In portfolio optimization as an example, it can be defined as threshold covariance among a cluster of financial instruments. Being able to select a pair of correlated instruments whose covariance is below the tolerable risk of the investor can be advantageous given the difficulties of finding large independent sets in an increasingly globalized stock market [5,6]. Since the Stable Set Problem has been shown to be NP-Hard [35], the ARM is also NP-Hard. Due to the computational difficulties that are typically associated with solving NP-Hard decision problems, the first methods that have been proposed for the ARM all involved the use of heuristic techniques to find good solutions (e.g., [3,7]). It was not until the early 2000s, when the first exact models of the ARM appeared in the refereed literature [4,27,34]. The first model in [27], called Path Formulation, enforces harvest opening size restrictions by means of constraints only. The formulation of these constraints, which are structurally very similar to the 0–1 cover inequalities in knapsack problems, requires the enumeration of all contiguous clusters of management units whose combined area just exceeds the maximum opening size. Subsequent attempts to improve the Path Formulation include [11] who appended knapsack constraints to [27]'s model to enforce area restrictions, [40] who proposed a strengthening procedure for the path constraints and [39] who showed that the use of path inequalities in lazy constraint pools can lead to dramatic savings in solution times.

The second exact model in [27], the Generalized Management Unit (GMU) or Cluster Packing Formulation also relies on an enumeration procedure [17,23,24,27,33]. Unlike the Path Formulation, however, which requires minimally infeasible clusters, it is the set of feasible clusters that are needed in this model. Feasible clusters are contiguous groups of management units whose combined area is less than or equal to the maximum opening size. The GMU model uses extra decision variables to represent feasible clusters that comprise more than one management unit. Pair-wise [27] or maximal clique-based [17] constraints can then be written to prevent the harvest of adjacent or overlapping clusters. [18] showed that the maximal clique-based Cluster-Packing Model provides a tighter approximation of the convex hull of the ARM than the Path Formulation and that it can produce superior computational results.

The third model, Bucket Formulation [9], is very different from the previous two in that it does not rely on apriori enumerations of feasible or infeasible clusters. Unlike the Cluster Packing models or the Path Formulation, this model uses harvest assignment variables instead of harvest variables. Any one management unit can be assigned to initially empty sets of *clear-cuts* or *buckets* [18] in every planning period. While the management units that are assigned to the same clear-cut do not have to be adjacent, constraints are in place to ensure that the total area of each clear-cut is less than or equal to the maximum harvest opening size. Finally, there are additional constraints in the model to prevent the formation of adjacent or overlapping clear-cuts. What makes the Bucket Formulation very attractive is that unlike the other two models, it does not require potentially costly enumerations and that the size of the model is limited by the number of feasible clear-cut assignments. While extra preprocessing is needed to identify "infeasible" assignments, the potential reduction in the number of variables and constraints can be substantial. That said, problem size for the Bucket Formulation can increase exponentially as a function of the number of units depending on the efficiency of the preprocessing algorithm.

1.2. Problem motivation

The size of the Path and the Maximal Clique-based Cluster Packing formulations is sensitive to the maximum harvest opening size, whereas the size of the Bucket model is sensitive to the number of management units. While problem size is not necessarily a good predictor of problem difficulty [41], it can make the problem formulation process prohibitively time-consuming, especially if cluster enumerations are involved. Moreover, solving large integer programs, such as the ARMs listed above, can also be hard [9,17]. These issues are never more apparent than in tradeoff analyses, where forgone timber revenues or changes in ecosystem metrics, such as forest habitat fragmentation, are to be forecasted as functions of alternative harvest opening size policies. Forest policy makers, landowners or forestry practitioners are all likely to be interested in how much compliance with a specific certification standard or a new regulation would cost. With the three existing ARM approaches, one has to formulate and solve a separate model for each opening size restriction of concern. This can be a time-consuming process if the forest in question has a large number of management units, or if the maximum harvest opening size is large relative to the average size of the units, or if many different harvest opening size policies are considered. Forest planning problems that involve thousands of management units are common. In fact, most authors argue that future research should focus on solving problems that comprise even more units (e.g., [17]). Forest regions across the globe, where the allowable clear-cut size is large are not uncommon either. In the Canadian provinces of Ontario and New Brunswick, in central and north Quebec, and in some regions of Alberta, as well as in Victoria, Australia and in Russia, the maximum opening size varies between 100 and 260 hectare [25]. In the Pacific Coastal states of Oregon and Washington, the limit is only 48.56 hectare but contiguous clear-cuts up to 97.12 hectare are allowed with special permission [25,43]. Very small management units are the norm in these regions, especially in the US private forest sector, where timber harvesting rights are typically allocated to willing buyers via auctions [2,38]. Small-scale buyers can bid only on small sales that contain lower timber volumes, and as a result, forest managers often design small units [36].

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