Extending Harvest-Scheduling Using Spatial Optimization: Road Access and Edge Effects.

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Abstract

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The scheduling of management actions across forest stands is a fundamental task in the world of forestry. However, the spatial and temporal layout of management actions can lead to a combinatorial explosion of potential options to consider. Additionally, these management alternatives must often meet various constraints and limitations. The sheer quantity of options quickly pushes these problems out of the realm of “eyeballing” a good, or even feasible, solution. Because of this, managers have turned to optimization models to help determine the best harvest schedule that meets all requirements. Due to the computational complexity of these models, managers are forced to make simplifying assumptions, and to limit the scope of the models to only the most fundamental aspects. Now, with continued progress in both computational power and solution techniques, it is becoming both practical and feasible to extend these harvest scheduling models to consider broader aspects of the process. In this dissertation I consider two major extensions to harvest scheduling models: road access and edge effects.

In chapter 1, I worked with the Washington State Department of Natural Resources to extend their harvest schedule modeling to consider the endogenous cost of rebuilding and maintaining the road network used to access a forest. I propose the Endogenous Fixed Charge Model (EFCM) to incorporate road costs that that vary endogenously with the system's harvest decisions. In a case study in the Pacific Northwest, the EFCM was integrated into DNR's standard workflows through the use of custom software called "Builder" that amended the EFCM constraints and variables to DNR's exiting harvest schedule optimization. Results from the case study show the EFCM was able to increase net present value over a million dollars and to reduce the overall road network by some 14%.

In chapter 2, I explore how edge effects between managed forest units can be controlled and mitigated. Newly created edges caused my management actions to alter the landscape and can affect many environmental factors. These altered environmental factors have a variety of impacts on forest growth and structure and can alter harvest yields and habitat for wildlife. After discussing how edge effects can arise from a variety of management actions, I propose a general optimization modeling framework to detect and flag newly created edges while determining an optimal management schedule. I use the real world context of clear-cut harvesting to illustrate multiple possible management objectives tied to the creation and delineation of newly formed edges. In a case study in the Pacific Northwest, I demonstrate how the modeling framework can be used to mitigate damage associated with increased wind exposure caused my neighboring harvests. Results from the case study show the modeling framework functions as intended and that a significant reduction in wind damage can be achieved by considering the spatial and temporal sequencing of harvest actions.

In chapter 3, I return to the road access problem to examine how an alternative representation of the road network affects the solution behavior of a joint harvest-scheduling and road-access model using route-finding. Route-finding removes the assumption of predefined routes and allows the optimization model to choose the best hauling route while considering all other harvests that need routing. The number of constraints and variables used for route-finding depend on the size and configuration of the road network. Therefore it is important to consider how alternative representations of the road network effect the solution behavior of these difficult-to-solve models. To test network representations, I propose a Mixed Integer Program (MIP) to include road-access using route-finding within a harvest-scheduling optimization. I apply this model to two different representations of the road network: the Traditional Spatial Representation (TSR) where roads are modeled as arcs connecting nodes, and the Line Graph Representation where roads are modeled as nodes, and arcs represent shared intersections. This transformation retains the same information as the original network, but can alter the number of nodes and arcs in the system. I illustrate the mechanics of the model in a case study in the Pacific Northwest and show that the LGR was able to outperform the TSR in many of the tested scenarios.

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Acknowledgments

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I feel incredibly fortunate to have found and been accepted into the Quantitative Ecology and Resource Management program. I have benefited greatly from collaborating and interacting with the amazing community that this small interdisciplinary program fosters. QERM was the only PhD program I applied to, and I couldn’t be happier with the choice.

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Lastly, this work is a culmination of an academic career supported by the public. Through public schools, assistance programs, state universities, and grants, my success was possible because society invested in me. For this, I offer my greatest thanks.

Dedication

To science!
Together, we can figure it out.

Chapter 1: Forest Harvest Scheduling with Endogenous Road Costs

1.1 Summary

The Washington State Department of Natural Resources (DNR) manages over 800,000 hectares of forested State trust lands and 20,000 kilometers of forest roads in Washington State. Scheduling decisions for forest management units regarding timber harvest and the reconstruction of forest roads for timber haul directly impacts the agency's cash flows and timber market access.

We introduce a mixed integer programming formulation that integrates harvest and road reconstruction scheduling decisions, and show how DNR embedded it in its standard forest industry workflows using a software application we created: Builder. We demonstrate the mechanics and the computational tractability of the model and report how it was implemented on the Upper Clearwater River landscape in the Olympic Experimental State Forest managed by DNR.

As applied on DNR-managed Olympic Experimental State Forest (OESF), DNR significantly improved the forest valuation of the Upper Clearwater River Landscape by $0.5-1 million (0.4-1.1% greater overall net present value). This is accomplished by concentrating capital expenditures in support of harvest and road operations in time and space leading to a 14.5% reduction in active road miles and associated environmental hazards.

As a result of these findings, DNR scaled the proposed model and the modified workflows to the entire 270,000 acre Olympic Experimental State Forest and is currently in the process of scaling up the model to its entire forest estate.

1.2 Introduction

Forest roads are an integral, yet expensive component of forest management (Greulich 2002). They are very different from other transportation networks in that they are typically viewed unfavorably by society. They are considered an eyesore in an otherwise pristine environment. This societal view is reflected in the regulatory environment that governs their use. Apart from their costs, forest roads also carry environmental risks such as increased risk of wildfires, sediment delivery (Bowker, et al. 2010, Bettinger, Sessions and Johnson 1998, Riedel 2004), the spread of pathogens (Jules, et al. 2002) and invasive species (Gelbard and Harrison 2003). In sum, forest roads are a financial and environmental hazard for timber companies. An increased road footprint comes with increased financial and environmental liability. Conversely, borrowing language from environmental economics, the spatiotemporal concentration of capital expenditures (forest roads) are expected to provide positive externalities. Despite high costs and environmental risks, practitioners generally consider road reconstruction only in tactical planning (1-10 years) based upon an already existing long-term (10-100 years) strategic harvest plan (Martell, Gunn and Weintraub 1998). As a result, road reconstruction is not coordinated with harvest scheduling, leading to lost opportunities.

Forest road construction and maintenance are generally regarded as capital expenditures of a “fixed” cost type that does not fluctuate with the amount of use or time. The classic fixed charge problem in operations research has been demonstrated to be a consistent approach for addressing these types of road decisions in harvest scheduling. However, because forest roads amortize as a capital asset and degrade over time, the fixed cost to maintain the road increases with the time since initial construction or last maintenance. This amount of time is in turn, a function of the harvest schedule itself, making the revenue and cost structure of the problem endogenous. Moreover, a given road segment may support timber haul from various locations resulting in a shared fixed cost situation. We refer to our problem as the Endogenous Fixed Charge Problem (EFCP) to distinguish it from the classic fixed charge problem (FCP) in operations research.

This chapter presents a solution to this problem in the form of a mixed integer program, which we shall hereby refer to as the Endogenous Fixed Charge Model (EFCM). Similar problems exist beyond forestry, primarily in fleet optimization and accounting of capital investments, such as vehicles, machines, and roads that deteriorate over time incurring gradually increasing maintenance expenses. Thus, our modeling contribution is applicable to a broad segment of industry.

Before providing a description of the EFCM, we summarize prior work on forest harvest and roads scheduling. We then demonstrate the mechanics and the utility of the EFCM and discuss its implementation by the Washington State Department of Natural Resources (DNR) on the Olympic Experimental State Forest (OESF) in the United States. We report how the proposed model was integrated with standard forest industry workflows in the context of DNR's information systems. Finally, we quantify the financial benefits of the model in the OESF and discuss its environmental implications as well as potential extensions.

1.1.1 Harvest Scheduling and Road Access

In forestry, management plans must address the long-term ecological and economic sustainability of the forest asset. They must mitigate end-of horizon effects (such as cutting too much upfront and leaving very little behind) and they must cover a sufficiently long time period to allow the forest to reach a desired steady state comprised of roughly the same number of hectares in each age class. This provides a diversity of habitat for wildlife from early to late successional stages, as well as a steady flow of timber products over time. To guarantee a harvest schedule is repeatable, the plan must be long enough to capture the natural periodicity of the system. This forces the forest industry to work with strategic plans that are at least 50 to 100 years long.

Creating plans 100 years into the future comes with large amounts of uncertainty. To help account for this, managers use positive discount rates and adaptive management practices whereby only the first-period harvest and road maintenance decisions are implemented. Periodically, new information about costs, prices and other inputs are taken into consideration and the model is re-optimized to generate new harvest schedules for the subsequent periods. Constraints, such as those that impose spatial restrictions, or even flows of harvest volumes or revenues, are used to ensure that that first-period management actions never compromise long-term sustainability concerns that aim to preserve the ecological viability of the forest ecosystem.

Up to the mid-1970s, harvest scheduling models documented in the literature considered road access only indirectly or hierarchically after the strategic harvest schedule had been made (Johnson and Scheurman 1977). The connection between the two decisions (roads and harvest) was ignored thereby incurring extra costs. Weintraub and Navon's mixed integer programming model (1976) was one of the earliest attempts to jointly optimize harvest scheduling and road construction and routing decisions. Due to the computational limits at the time and the complexity of the problem, the authors tested their model only on very small, illustrative data sets. The Integrated Resource Planning Model or IRPM (Kirby, et al. 1980) was a much more robust planning tool that integrated the two decisions. To demonstrate the financial savings of integrating road construction decisions with harvest scheduling, Jones et al. (1991) compared the IRPM to a decoupled model (a model that optimized the harvest schedule first, and then optimized the road network). Using real-world datasets, Jones et al. found that the IRPM's solution was significantly higher (up to 43%) in net present value, than the decoupled model.

The previous studies focused on the construction and planning of new roads, not on the maintenance of an existing road network. Examples of optimization models in forestry that accounted for road maintenance included Bettinger et al. (1998), Karlsson et al. (2004) and Olsson and Lohmander (2005).

With pre-calculated shortest routes – contiguous sets of road segments that connect forest management units (FMUs) with demand or processing points or landings, Bettinger et al.'s model incorporated road maintenance decisions to meet sediment delivery goals and protect aquatic habitat. Unlike the EFCM, however, the maintenance costs did not change and were not specific to segments.

Karlsson et al.'s (2004) model optimizes the transportation of specific quantities of raw timber to sawmills while allocating work crews and machinery to maintain the road network. In Karlsson's model, the road maintenance cost varied externally by season, and the focus was resource distribution, not harvest scheduling. Lastly, Olsson and Lohmander (2005) sought to minimize the total cost of transport and road investments over a planning horizon of 10 years while maintaining an acceptable and stable supply of round wood for mills to use. The Olsson and Lohmander model selects the areas to harvest during different seasons. The selection affects the costs of road investments and round wood transport during the thawing period in the spring. The focus of this model is on the maintenance of one particular type of road (gravel) and the movement and storage of harvested wood. Like Karlsson et al.'s model, the fixed costs varied exogenously with the four seasons and did not change based on the current state of the road system.

Most of the harvest scheduling models that account for road costs or integrate road maintenance decisions (e.g., Weintraub and Navon 1976, Bettinger, Sessions and Johnson 1998) are extensions of the classic Fixed Charge Problem (FCP) of operations research, which has been shown to be NP-hard (Maniezzo and Paruccini 1998). The proposed EFCP also falls into this category of computational complexity. The difficulty of finding optimal solutions to integrated harvest scheduling models has led many researchers in the past to use heuristics methods. These included simulation (Weintraub and Cholary 1991), the interchange method (Murray and Church 1995), simulated annealing (Chung and Sessions 2003, Murray and Church 1995), tabu search (Richards and Gunn 2000, Murray and Church

1995, Bettinger, Sessions and Johnson 1998), ant colony optimization (Contreras, Chung and Jones 2008), heuristic integer programming (Weintraub, et al. 1994), and great deluge (Chung and Sessions 2001).

In conclusion, the endogenous nature of the revenue and cost structure of the EFCP has not been addressed in forestry. With our proposed EFCM, we overcome this shortcoming by integrating the EFCM with established forest industry workflows. Not only do we expect overall revenues to increase from taking advantage of the shared fixed costs, but we also hope that the roads will be used more efficiently, thereby reducing environmental risks.

1.1.2 Key Assumptions of the EFCM

We postulate a couple of assumptions that are necessary for embedding EFCM into standard forest sector workflows. First, typically there are two different types of road costs associated with harvest scheduling: reconstruction and maintenance costs. Road reconstruction costs are determined *a priori* for each road segment and are representative of the design specifications that accommodate the anticipated traffic levels, lifespan, and regulatory requirements. Road reconstruction includes major repairs or upgrades that typically address obsolescence in design specifications and degradation over time. These decisions represent improvements with long lifespans including culverts and bridges. Road reconstruction incurs a “shared fixed cost” with regard to timber haul. It is a fixed cost because it does not vary with the amount of timber hauled on the segment and the reconstruction project must be completed in its entirety before any haul can occur. It is a shared cost because the timber to be hauled on the segment can originate from multiple FMUs with timber revenues that can all contribute to cover the costs. A road segment is considered to be either up to standard or not. If it is not up to standard, then timber haul is prohibited.

Unlike reconstruction, maintenance incurs a variable cost. These costs increase with production across tributary FMUs within the road network. Maintenance addresses surfacing and minor repairs due to run-off and wear and tear and therefore its costs cannot be determined *a priori*. In this chapter, we will assume that these costs are insignificant for harvest scheduling problems with long planning horizons and multi-year planning periods. Long planning horizons generally exceed the useful lifespan of road improvements and multi-year planning periods require generalized accounting of intra- and inter-period cash flows. Moreover, variable maintenance costs are typically very small relative to reconstruction expenses that involve major projects.

Lastly, we assume that the least-cost route through the road network to access each FMU is predetermined using Geographic Information System (GIS) tools such as Spatial Analyst (ESRI). While this assumption prevents the model from dynamically constructing the hauling routes via optimization, it imposes no restrictions on the network of forest roads that can be used as input for the model. We reduce the input road network to only the segments included in the least-cost hauling routes. This assumption was necessary to emulate standard forest industry practices. Although this assumption was required for this analysis, we also present an alternate formulation of the model that can dynamically determine routing during optimization instead of relying on predefined routes.

1.1.3 An Example of Endogenous Fixed Cost Savings

To demonstrate the potential savings associated with integrating endogenous road reconstruction costs with harvest scheduling, consider the following three models: hierarchical, classic fixed charge (FCP), and the EFCP. While the hierarchical model ignores road costs, the FCP and EFCP do not. The difference between the FCP and the EFCP is that the former assumes that the fixed costs are static. The EFCP accounts for both the fixed cost component of road reconstruction and the endogenous costs that increase over time due to amortization.

To compare the three models, suppose the segments serve eight silviculturally and financially identical FMUs over a time horizon of four planning periods. FMUs 1 through 4 share road segment A, and FMUs 5 through 8 share road segment B (Fig. 1). Suppose also, that management allows for the harvest of only two FMUs in each planning period. We assume that roads must be upgraded, for a cost of α, before they can serve an FMU. Lastly, suppose that reconstruction costs only 0.5α if it follows the prior reconstruction in the subsequent planning period.

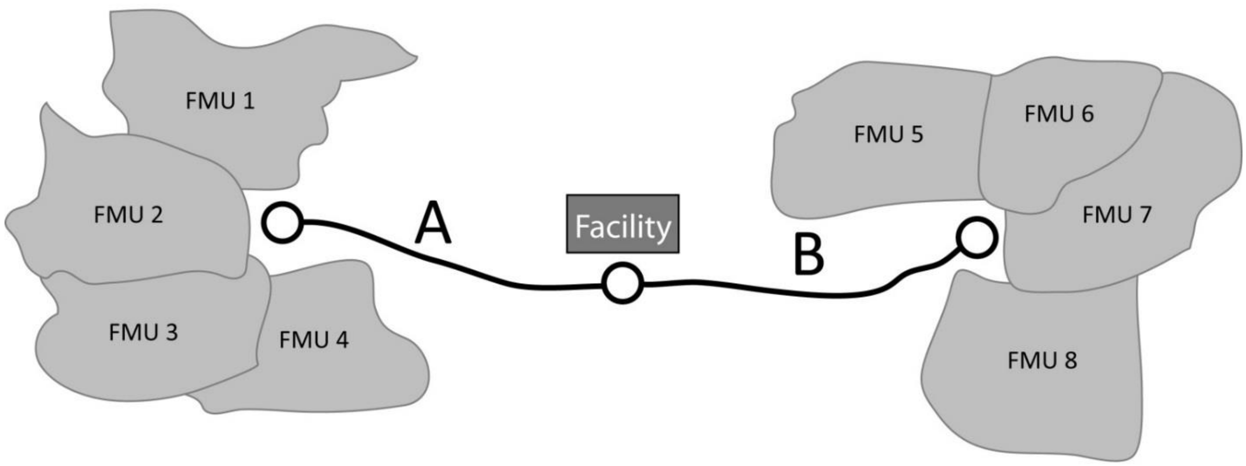

Figure 1-1: Hauling routes for FMUs that share common road segments.

Table 1 lists the optimal solutions corresponding to the three models. Because all FMUs are identical in this example, any solution to the hierarchical model that harvests each of the eight FMUs over the four periods is optimal, including the one listed in Table 1. The hierarchical model's optimal schedule requires that both of the roads are reconstructed in all four periods incurring a total of 5α in costs. The harvest schedules given by the FCP model are spatially concentrated in each period to minimize road costs. For the FCP model, any schedule that rebuilds only one road in each period is optimal leading to 4α in costs. Lastly, the EFCM concentrates harvests spatially in each period as well as across periods. By concentrating harvests over time, the EFCM takes advantage of lower reconstruction costs associated with a recently reconstructed road. The optimal solution presented in Table 1 for the EFCM has a road cost of 3α—the lowest found among the three models.

	Hierarchical Model			FCP Model			EFCM		
Period	**FMU**	**Road**	**Cost**	**FMU**	**Road**	**Cost**	**FMU**	**Road**	**Cost**
1	1,8	A,B	2α	1,2	A	α	1,2	A	α
2	4,5	A,B	α	7,8	B	α	3,4	A	$.5\alpha$
3	2,7	A,B	α	3,4	A	α	5,6	B	α
4	3,6	A,B	α	5,6	B	α	7,8	B	$.5\alpha$
Total:			5α			4α			3α

Table 1-1: Optimal harvest schedules under the hierarchical, FCP, and the EFCM models.

1.3 EFCM Formulation

We formulated the EFCM as a mixed integer program. The objective of the model is to maximize net present value associated with harvesting while accounting for endogenously driven road reconstruction costs over a time horizon of multiple planning periods. The model requires that all road segments that comprise the hauling route associated with a given FMU must be reconstructed in the planning period in which the FMU is scheduled to be harvested. Again, we assume that the least-cost hauling route for each FMU is found *a priori*.

The cost to reconstruct a road segment is determined by the cost of full reconstruction, α, and parameter ϕ_j that scales α into J price tiers representing the decrease in cost that occurs because of recent reconstruction. If road segment i has not been used for J periods prior to the scheduled haul, full reconstruction is necessary, which incurs cost α_i (and thus $\phi_J = 1$). If the road segment was reconstructed in the previous period, then it requires less than the full reconstruction cost; $\phi_1\alpha_i$. Similarly, if the road was reconstructed two periods prior, it requires $\phi_2\alpha_i$. Because the ϕ parameters are a discrete set of multipliers, we can assign any desired form of cost decrease to them as long as $\phi_1 < \phi_2 < \ldots < \phi_J$.

The full mathematical representation of the EFCM model is detailed below:

The EFCM Model

$$\text{Max} \sum_{m,t} \rho_{m,t} x_{m,t} - \sum_{i,t,j} \phi_j \alpha_i s_{i,t}^j 1.05^{(5-10t)} \quad (1)$$

Subject to:

$$\sum_j s_{i,t}^j \leq 1 \qquad \forall\, i, t \quad (2)$$

$$\sum_{i \in S_m} \sum_j s_{i,t}^j \geq |S_m| x_{m,t} \qquad \forall\, i, t \quad (3)$$

$$\sum_{k=1}^{J} s_{i,t-j}^k \geq s_{i,t}^j \qquad \forall\, i, t, j \quad (4)$$

$$x_{m,t} \in \{0,1\} \qquad \forall\, m, t \quad (5)$$

$$s_{i,t}^j \in \{0,1\} \qquad \forall\, i, t, j \quad (6)$$

where the decision variables are:

$x_{m,t} = 1$ if FMU m is to be harvested in period t, 0 otherwise; and

$s_{i,t}^j = 1$ if road segment i is to be reconstructed in period t at the cost of $\phi_j \alpha_i$, 0 otherwise.

The sets are:

$M =$ the set of all FMUs with $m = 1,2, \ldots, |M|$;

$I =$ the set of all road segments with $i = 1,2, \dots, |I|$;

$S_m =$ the set of road segments in the least-cost hauling route for FMU m; and

$T =$ the set of 10-year long planning periods indexed by $t = 1,2, \dots, |T|$. Harvests and road reconstruction activities are assumed to occur in the mid point of the planning periods.

The parameters are:

$\rho_{m,t} =$ the net discounted timber revenue associated with harvesting FMU m in period t;

$J =$ the total number of cost tiers;

$\phi^j =$ the fraction of full reconstruction cost required for a road segment that was last reconstructed j periods earlier; and

$\alpha_i =$ the total reconstruction cost of road segment i. Parameter α_i is assumed to remain constant in real value throughout the planning horizon.

The objective function (1) maximizes the discounted net revenues associated with the management of $|M|$ units over a planning horizon of $|T|$ planning periods. The first term accounts for the discounted net harvest revenues, whereas the second term accounts for the road reconstruction costs, assuming a 5% discount rate.

Inequalities (2) and (3) ensure that if FMU m is harvested in time t, then all road segments in the least-cost hauling route for FMU m (S_m) must be up to regulatory standard by time t. Inequality (2) requires that only one of $s_{i,t}^1$, $s_{i,t}^2$,..., $s_{i,t}^J$ can be activated in each time period. If a segment is reconstructed, only one cost is incurred. If all s variables are zero, the road segment has not been reconstructed and no cost is incurred. Inequality (3) compares the number of reconstructed segments in a unit's least-cost hauling route to the total number of road segments in the route. If any one of the road segments in the least-cost route is below regulatory standard, then $x_{m,t}$ is forced to take the value of zero. Thus, for a harvest to occur in time t, all roads that lead to the FMU must be up to regulatory standard in time t.

Inequalities (4) represent the endogenous cost structure and control the values that variable $s_{i,t}^{j}$ can take in a given period. Inequality (4) allows $s_{i,t}^{j} = 1$ only if the segment has been reconstructed in period $t - j$. There is no restriction on variable $s_{i,t}^{J}$, however, as this variable represents the full cost of reconstructing the road segment and is used if reconstruction has not occurred for J or more periods. The cost-minimizing objective function will force the model to choose the lowest available cost tier.

Finally, inequalities (5) and (6) declare the decision variables as binary.

1.1.4 Workflow Integration

We show how the proposed EFCM was integrated with standard workflows of the Washington State Department of Natural Resources. DNR manages over 800,000 hectares of forested State trust lands and 20,000 kilometers of forest roads in Washington State. “As a trust land manager, DNR is obligated to follow the common law duties of a trustee which include generating revenue, managing trust assets prudently, and acting with undivided loyalty to trust beneficiaries” (County of Skamania vs. State, 1984). DNR “relies primarily on net present value as the most comprehensive and direct way to measure financial returns to the trusts and evaluate investments” (PSF 2006). Scheduling decisions for forest management units regarding timber harvests and the reconstruction of forest roads for timber haul directly impacts the agency's cash flows. Currently, DNR develops harvest schedules using industry standard forest planning software, Remsoft’s Woodstock (2013). Road reconstruction decisions are made only after the harvest schedules are set using Woodstock.

We show how DNR integrated EFCM in its workflows using a widely adopted commercial software package called Woodstock. DNR relies on Woodstock to generate a linear program that captures every aspect of forest planning (such as even harvest flows, ending inventory constraints and so on) except forest road reconstruction decisions. Our goal was to add additional constraints and variables to the existing Woodstock formulation to embed the functionality of the EFCM in the harvest scheduling model. The mathematical model used by WoodStock is known as Model II (Johnson and Scheurman 1977), and is formally described in Appendix II. The linear programming formulation of Model II specifies how many hectares of each FMU are to be cut in a given planning period. Linking the EFCM's binary harvest indicators with the fractional harvest variables of Model II requires introducing a pair of "trigger" constraints,

$$\sum_{k=-M}^{t-Z} W_{m,k,t} \geq H_{min}\, x_{m,t} \qquad \forall\, m, t \tag{7}$$

and

$$\sum_{k=-M}^{t-Z} W_{m,k,t} \leq H_{max} x_{m,t} \qquad \forall\, m, t \qquad (8),$$

in order to ensure that the binary harvest indicators from the EFCM will take the value of 1 whenever a minimum amount of area is scheduled to be harvested from an FMU. Here H_{min} and H_{max} are the minimum and maximum threshold values (H_{max} is simply an upper bound on the areas of the units) to turn on or off $x_{m,t}$, and $W_{m,k,t}$ is the continuous harvest variable from Model II. It is important to mention that Inequalities (7) and (8) enforce a minimum area that must be harvested within an FMU if it is to be harvested at all. If the right-hand side of Inequality (8) is greater than 0 but less than H_{min}, then the model becomes infeasible because Inequality (8) will force $x_{m,t} = 1$ while Inequality (15) will force it to be 0. Lastly, we also modify the revenue coefficients in the objective of the EFCM to be a function of the continuous harvest variables $W_{m,k,t}$.

By linking the continuous harvest variables from Model II to the binary decision variables of the EFCM using the binary indicator variables, we create a Mixed Integer Program (MIP). The approach simultaneously maintains all the functionality of Model II while taking into account the costs of road reconstruction during optimization as provided by the EFCM. Functionally, we amend the constraints and variables required of the EFCM to DNR's existing linear programming matrix. Doing so, we convert a largely aspatial model to a spatiotemporal one that not only integrates harvest and road scheduling decisions but it also allows the managers to see and control specific actions at specific locations on the landscape at specific times. And, we do this with very little computational overhead, which is why our model made its way into DNR's standard workflows.

We developed software named Builder that adds the EFCM into DNR's standard workflow. Fig. 2 illustrates the workflow without, and with Builder. Currently DNR uses Woodstock to formulate the harvest scheduling models in the format of an LP matrix, which is then given to an IBM integer programming solver called CPLEX. CPLEX then returns a solution to Woodstock for interpretation (Fig. 2A). Woodstock uses the solution to output an easily interpretable harvest scheduling plan, as well as multiple graphs, charts, and other visualizations. This output allows managers to test what-if scenarios, and to demonstrate possible outcomes to engineers, stake-holders and the public. Managers use this output as the basis of decadal sustainable harvest calculations.

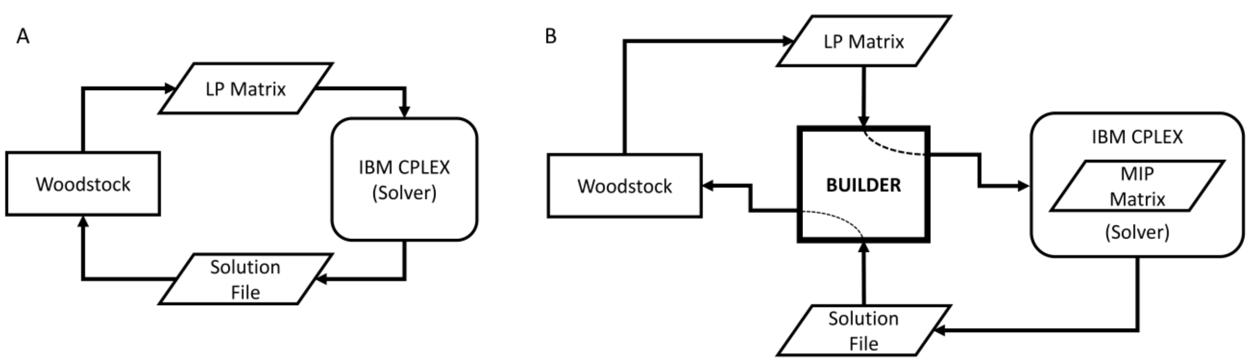

Figure 1-2: (A) Old DNR workflow (B) New workflow with Builder.

When using Builder, the workflow still begins and ends with Woodstock. Woodstock generates the same LP matrix, but it is intercepted by Builder while being passed to CPLEX. The LP matrix is modified by adding the proposed road network and trigger constraints after being intercepted. Builder modifies the matrix (now a mixed integer program) inside the CPLEX environment for convenience. Once modified, CPLEX solves the model and returns a solution file to Builder. Builder then creates custom outputs and prepares the solution file for interpretation by Woodstock, the same way as before (Fig. 2B).

1.1.5 Control Model

To measure the financial benefits of the integrated EFCM on DNR trust lands, we created a control model that calculates but does not minimize road costs for each potential solution. The control model is analogue to the Model II formulation created by Woodstock in that it mimics the solution that would be gained without the EFCM. The difference is that our control model calculates the road costs automatically without having to post-process the Model II solution for road use. It establishes a benchmark net present value against which we can compare the performance of EFCM.

To create the control model, we modify the EFCM. First, to ensure that the control model ignores the roads costs during optimization, we remove the road costs from the objective function (1) of the EFCM. Second, since the objective function of the control is not needed to minimize road costs, we must add inequalities to force the control model to use the cheapest possible $s_{i,t}^{j}$ variable to rebuild a segment. Otherwise, the costs would be overestimated. To accomplish this, we add inequality (9):

$$s_{i,t}^{j} + \frac{1}{j-1}\sum_{p=1}^{j-1}\sum_{k=1}^{J} s_{i,t-p}^{k} \leq 1 \qquad \forall\, i,\ t, j > 1 \qquad (9)$$

Inequalities (9) and (4) work in concert. Inequality (4) allows, while inequality (9) forces, the use of the lowest available cost tier. In other words, these inequalities do not allow $s_{i,t}^{j}$ to activate if the road segment was reconstructed fewer than j periods prior to t, and therefore qualifies for a lower cost than ϕ_j. Together, these inequalities force the optimal choice of $s_{i,t}^{j}$ variables without relying on a cost minimizing objective function.

Similarly, without minimizing costs, the control model could potentially reconstruct road segments that are not needed. To avoid this, we need additional inequalities that only allow $s_{i,t}^{j} = 1$ if an FMU that contains segment i in its hauling route is harvested in period t:

$$\sum_{m \in I_m} x_{m,t} \geq \sum_{j} s_{i,t}^{j} \qquad \forall i, t \qquad (10)$$

where I_m is the set of all FMUs m that have segment i in their least-cost hauling route. These inequalities work as the counterparts of inequality (3). Inequality (3) requires that all roads in a FMUs hauling route be up to regulatory standard in the period the FMU is harvested. Conversely, inequality (10) only allows a road to be reconstructed if an FMU that uses it is harvested.

Finally, we store the road costs in accounting variables using an equality (11). The accounting variable (*RoadCost*) simply adds up the road costs required by the harvest decisions that are found to be optimal by the control model without having any impact on the harvest schedules.

$$\sum_{i,t,j} \phi_j \alpha_i s_{i,t}^{j} 1.05^{(5-10t)} - RoadCost = 0 \qquad (11).$$

1.4 The Application of EFCM in the Pacific Northwest United States

We applied the proposed EFCM to the Washington DNR's Upper Clearwater River landscape located on the western slopes of the Olympic Peninsula in the Pacific Northwest United States (Fig. 3). The Upper Clearwater contains 621 operable FMUs served by an existing road network of more than 6,000 road segments, and is part of the Olympic Experimental State Forest (OESF). The management objective is to maximize net present value over a 100-year long planning horizon, divided into ten 10-year long planning periods. Managers must determine harvest regimes for each FMU to maximize NPV while meeting long-term sustainability constraints, such as even flow of revenues and harvest volumes

(Inequalities (A5) and (A6)), as well as ending inventory and ending age requirements (Inequality (A7)). Both the 100-year long planning horizon and the 10-year long planning periods are standard for the forest sector. The 10-year long periods provide sufficient flexibility for the agency to schedule harvest activities on an annual, tactical basis to make the best use of changing market conditions and in the face of unforeseen weather events. Lastly, the minimum rotation age was set to a regionally representative 40 years.

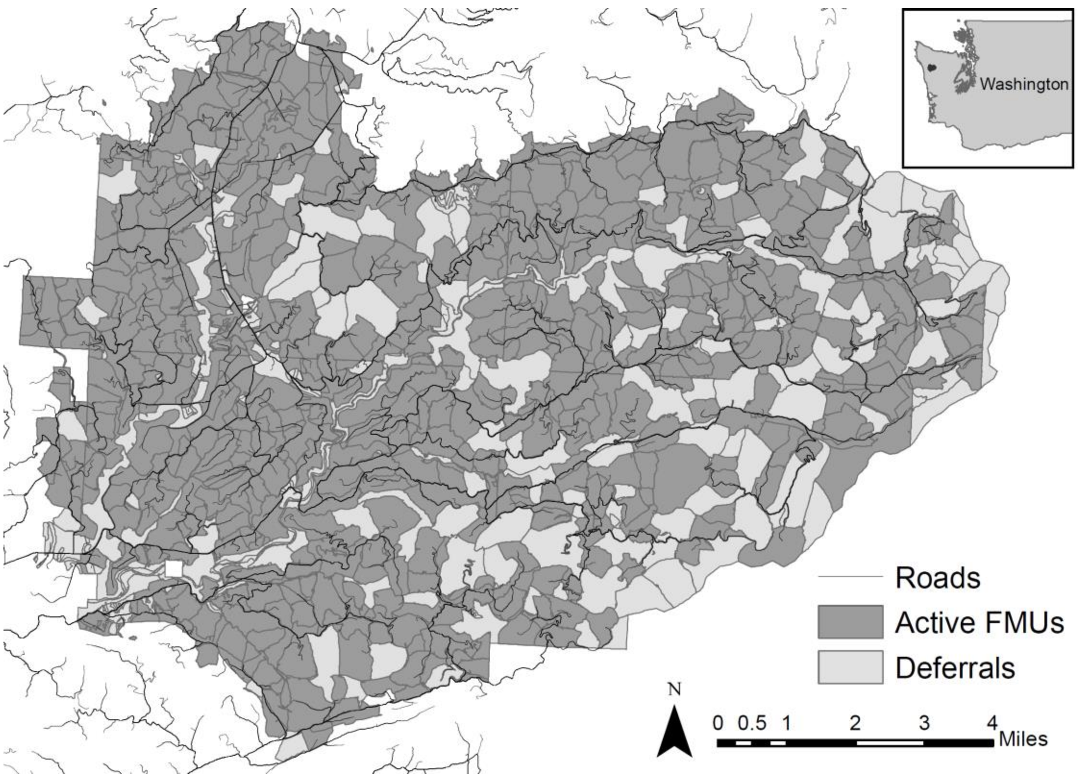

Figure 1-3: The Upper Clearwater Landscape**.**

Although the OESF is a member of a national network of experimental forests, it is a key component of DNR's commercial land-base. The right to harvest forest stands on DNR land is allocated competitively via auctions where the highest bidders get to cut and haul the designated timber. Sharing OESF-specific spatial information is harmless for the Agency, however, disclosing economic or growth and yield data that are more broadly relevant beyond the OESF can compromise DNR's operations. In the next section we describe how the EFCM was parameterized and implemented on the Upper Clearwater landscape.

1.1.6 Parameterization and Data

For the Upper Clearwater, DNR assumed that roads degrade linearly over a 30-year period. This means that a road not used for timber haul for 30 years or more requires full reconstruction, whereas a road last used between 20 and 30 years ago costs one third less and one last used between 10 and 20 years ago costs two thirds less in real terms. Under this assumption, we set $\phi_3 = 1,\ \phi_2 = \frac{2}{3}$, and $\phi_1 = \frac{1}{3}$. The maximum allowable harvest, H_{max}, was set to the area of the FMUs, which places no restrictions on harvests. The minimum allowable harvest, H_{min}, was set to the equivalent of $25,000, preventing harvests that were deemed to be unreasonably small.

Due to the importance of roads, it is common for the forest industry to have a well maintained roads database. To leverage this, information about the road network, including the spatial layout and the cost to fully reconstruct each segment (α), was taken from DNR's previously maintained roads database. Least-cost routes were found *a priori* for each FMU using GIS. The initial age-class distribution, growth estimates, and projected discounted net timber revenues of the FMUs came from the Woodstock formulation (Model II). This formulation also included harvest flow and ending inventory constraints. Harvest flow constraints determine the maximum allowable increase and decrease in harvest volumes between adjacent periods (both 25% here). These constraints help create a stable revenue stream and product supply by not allowing drastic swings in production. Ending inventory constraints require the area-weighted average age class of the forest at the end of the 100-year long planning horizon to be at least as large as it was in the beginning of the planning horizon. These constraints prevent over harvesting, and in conjunction with the harvest flow constraints, create a diversity of forest age classes.

To help determine the feasibility and practicality of scaling the EFCM to larger forest networks, we applied the EFCM to multiple datasets. We used the following datasets to analyze the solution behavior and the computational performance of the EFCM: the entire Upper Clearwater dataset (621 FMUs, referred to as the full dataset) and three subsets of the Clearwater dataset (91, 193, and 299 FMUs, referred to as the small, medium, and large data subsets, respectively). Each of the subsets are served by only one *mainline* (or exit node, sink node or *facility* in operations research terminology). In forest management applications, “facilities” or sink nodes often refer to paved state or county roads that are always up to standard from the industry’s standpoint (“mainlines”). These roads are used to haul the timber to sawmills or to ports for processing or for further transportation (demand points). The hauling routes associated with the FMUs within each subset of the Upper Clearwater dataset overlap, creating opportunities for fixed road cost savings (Fig. 4).

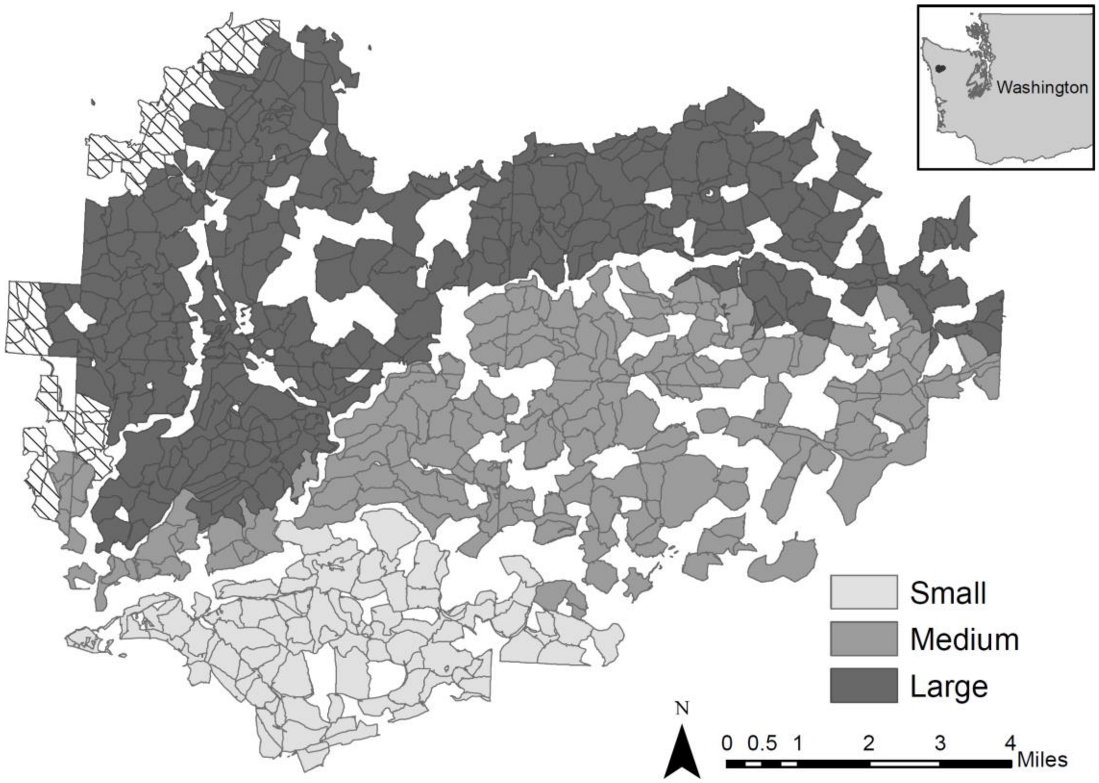

Figure 1-4: The three divisions (subsets) of the Upper Clearwater River landscape used in the computational study.

We solved the EFCM model and the control for all datasets using IBM ILOG CPLEX 64-bit 12.1.0 on a Dell Power Edge 510 Server with Intel Xeon CPU, X5670@2.93 GHz (2 processors) with 32 GB of RAM and the Windows Server 2008 64-bit operating system. The control model was solved to full optimality for all datasets while the EFCM was solved to a 1% optimality gap allowing for a conservative estimation of the financial benefits of EFCM. Default values were used for all other CPLEX parameters.

The objective function values (net present value), optimality gaps, and solution times were recorded for subsequent analyses. From the solutions, we calculated the number and the length of reconstructed road segments and converted the volume of timber to be hauled into average daily truck passes to proxy the environmental benefits of the EFCM. We also measured the spatial concentration of harvests in two ways.

First, we calculated the average distance of a harvested FMU to a set number of nearest neighbor FMUs that were also harvested. For each FMU, we identified the smallest radius circle that captured the FMU centroid as well as a set number of other FMU centroids harvested in the same period. Then, we averaged the radii of the circles across all FMUs to determine the average distance to the nearest 5, 25, and 100 harvested neighbor FMUs for the full dataset (Table 3).

Second, we calculated the spatial concentration of harvests based the average number of truck passes per day for each road segment required for timber haul under the EFCM vs. the control model solutions for the full dataset. For each period, we summed the total harvest volumes to be hauled across each road segment. We converted these values to average truck passes per day by using 4,800 board feet of timber as a truckload and assuming two passes per truck (one empty and one full).

We also investigated how the solutions respond to an unforeseen shock event related to road reconstruction costs (ϕ). These shocks emulate environmental disturbances such as massive storms that would damage or destroy parts of the infrastructure, thereby dramatically increasing reconstruction costs. The EFCM has a financial incentive to invest in road maintenance if the present value of the endogenous reductions in future reconstruction costs exceed that investment. Thus, we test the robustness of the EFCM solutions to unforeseen events that would damage the road network thereby increasing costs dramatically. We simulate the shock to the road network by requiring full reconstruction costs for all road segments rebuilt after the event regardless of when these segments were used prior to the event. We then recalculate the road costs for both the EFCM and the control model solutions to see how they compare in the face of the unforeseen shock event.

1.5 Results

Table 2 lists the solution times, the number of road segments as well as total road length required for haul, the objective function values, and the optimality gaps for the three datasets for both the EFCM and the corresponding control models. We report the difference between the objective function values of the EFCM and those of the control model. When provably optimal solutions were not available, we report the difference between the upper bounds of the EFCM objective values and those of the control models' to provide a conservative estimate of the financial savings.

Dataset	**Small**	**Medium**	**Large**	**Full**
Number of FMUs	91	193	299	621
Number of Road Segments	107	214	337	696
EFCM Solve Time (s)	46	416	1077	9964
Control Solve Time (s)	2	14	34	36
EFCM Reconstructed Road Segments	517	1186	1722	3604
Control Reconstructed Road Segments	624	1336	2038	4141
EFCM Total Reconstructed Road	502,700 ft.	946,192 ft.	137,4042 ft.	2,959,438 ft.
Control Total Reconstructed Road	620,892 ft.	1,076,584 ft.	1,651,969 ft.	3,463,099 ft.
EFCM Objective Function Value	$13,031,836	$32,286,807	$38,846,612	$86,711,336
Control Objective Function Value	$13,010,742	$32,119,611	$38,752,708	$86,299,566
Minimum Difference	$21,094	$167,195	$93,903	$411,769
Upper Bound	$13,155,500	$32,526,500	$39,224,700	$87,263,600
Upper Bound on Difference	$144,757	$406,888	$471,991	$964,033

Table 1-2: A comparison of the performance of the EFCM and the control model.

The EFCM solved to 1% optimality gaps in reasonable time for all datasets. The most difficult instance was completed in less than three hours. The control model solved to full optimality in less than a minute for all datasets. While many factors, including the spatial configuration of the FMUs and the road network, might influence solution times, from the Upper Clearwater application we observed for both the EFCM and the control model that doubling the number of FMUs increased solution times by approximately a factor of ten.

In terms of objective function values, the EFCM performed better even with 1% optimality gaps than the control at full optimality. If the EFCM was run longer, the solver might improve the objective values even further. For the full Upper Clearwater dataset, the EFCM saved 10.4% on road costs, increasing overall net present value by 0.4-1.1% as compared to the control model.

The EFCM generated harvest schedules with higher objective function values and fewer required roads. In the full Upper Clearwater dataset, the EFCM reconstructed 14.9% fewer road segments than the control. In terms of the total road length, the EFCM reconstructed 14.5% less than the control. In other words, the EFCM used roads more parsimoniously in a spatially concentrated pattern. Fig. 5 shows the FMUs harvested in Period 1 and Period 10 under both the EFCM and the control model solutions. In Period 1, the spatial distribution of FMUs harvested by each model is very similar. However, by period 10, that distribution is markedly different: the harvest allocation is much more concentrated with the EFCM. We expect these spatiotemporally concentrated harvest patterns to lead to more spatially contiguous forest patches in similar successional stages than the less concentrated harvest patterns found in the control model solution.

Average Distance to Nearest Neighbors (feet)			
Number of Neighbors	**5**	**25**	**100**
EFCM Model	1075.25	3584.05	8680.90
Control Model	1226.88	4161.78	10729.08

Table 1-3: Average distance to nearest neighbors for the full Upper Clearwater dataset in Period 10.

This result is also supported by the parallel findings that the EFCM has (1) a consistently lower average distance for each set number of nearest neighbors harvested (Table 3), and (2) fewer road segments with a low, and more segments with a high, number of daily truck passes as compared to the control model (Table 4). The latter finding suggests that the EFCM concentrates timber hauling on a fewer number of road segments than the control model. Assuming that segments not scheduled for use are ablated, the net environmental impact of the network can be reduced (Bowker et al. 2010).

Average Number of Daily Truck Passes	<1	1-2	2-3	3-4	4-5	>5
Number of road segments (EFCM)	2286	402	157	143	166	417
Number of road segments (Control)	2757	457	286	145	108	388
Difference	-471	-55	-129	-2	58	29

Table 1-4: Number of daily truck passes expected for each segment under the EFCM and Control solutions.

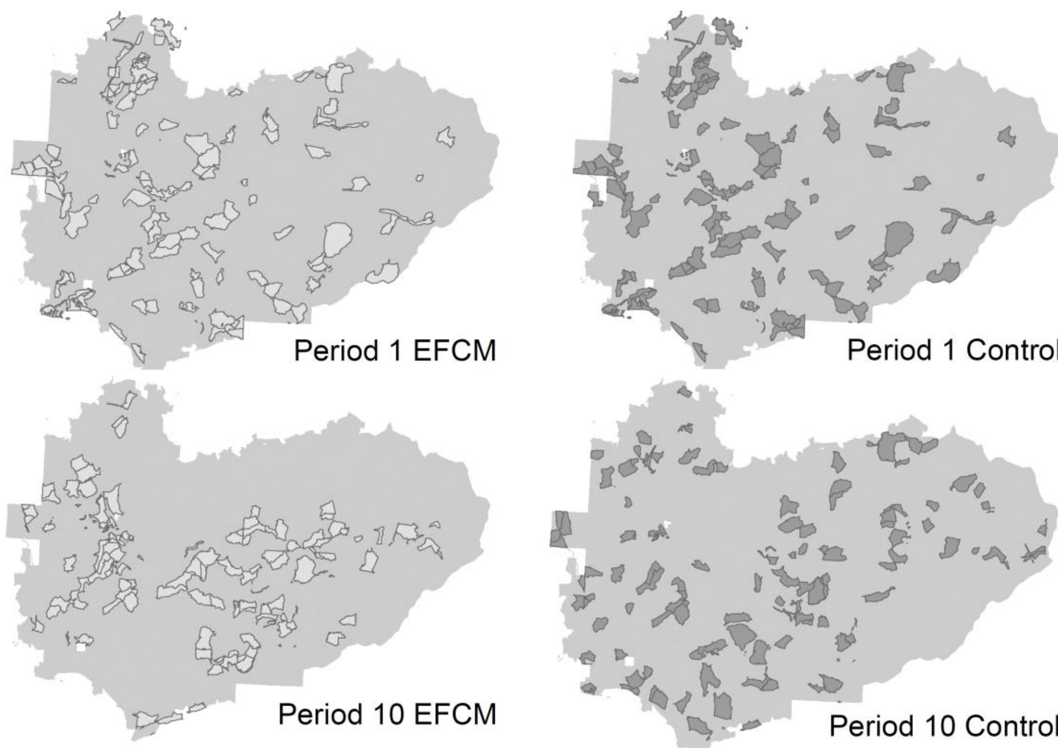

Figure 1-5: Comparison of FMUs harvested in Period 1 and Period 10 under the EFCM (light polygons) and control model (dark polygons) solutions.

Additionally, we found the EFCM solution to be more robust to unforeseen shock events related to road reconstruction costs than the control model. Table 5 lists the percent increase in road costs caused by a simulated network wide shock event. In all cases, the shock results in greater increases of road costs in the control model then in the EFCM.

Shock Between Periods	1-2	2-3	3-4	4-5
EFCM Road Cost Increase	23.88%	13.03%	9.63%	6.26%
Control Road Cost Increase	25.06%	17.59%	10.72%	6.60%

Table 1-5: Increase in road costs caused by a simulated shock to the road network.

1.6 Discussion and Conclusions

In this chapter, we introduced an operations research problem called the Endogenous Fixed Charge Problem (EFCP) that arises in forestry because of the endogenous nature of the revenue and cost structure of forest management decisions. We proposed a mixed integer programming formulation called EFCM to address the EFCP for forest roads. We integrated the EFCM directly within typical forest industry standard workflows using commercially available software.

As applied on DNR-managed Olympic Experimental State Forest (OESF), DNR significantly improved the forest valuation of the Upper Clearwater River Landscape by $0.5-1 million (0.4-1.1% greater overall net present value). This is accomplished by concentrating capital expenditures in support of harvest and road operations in time and space leading to a 14.5% reduction in active road kilometers and associated environmental hazards. Additionally, we expect higher auction revenues and increased participation as bidders notice that the new pairings of timber sales would allow them to reduce road costs by spatially and temporally concentrating harvest patterns. Since the EFCM can be easily embedded in existing workflows (as we have demonstrated), we do not anticipate any changes to normal planning efforts or field operations that already leverage harvest schedules. Overall information management can remain unchanged with our proposed model.

As a result of these findings, DNR is currently scaling the modified workflows to the entire 110,000 hectare Olympic Experimental State Forest and in time to the entire forest estate. In collaboration with the University of Washington's Precision Forestry Cooperative, DNR organized a successful outreach to practitioners of Washington's forest industry; demonstrating Builder as a leading analytical framework that bridges a perceived gap between best available science in OR and industry's harvest scheduling workflows.

We identify several limitations as recommendations from improving the precision of the EFCM for the forest roads problem. We recommend generalizing the EFCM to address multiple road decisions including the complete removal of road segments from the network when found to be redundant by the optimization model, varying the rates of depreciation, limiting the spatiotemporal concentration of timber harvests, and identifying least costs routes dynamically rather than *a priori*.

As for the applicability of EFCM beyond harvest scheduling, we emphasize that forestry is not the only industry that faces the conundrum of increasing maintenance expenses due to amortization. The core concept of roads degrading over time is a widely held assumption. For example, the state of Mississippi considers all roads to degrade down to 20% salvage value over 20 years [MOSA 2002]. Internationally, the Southern Australia Local Government assumes road sealant degrades linearly over 10 years [SALG 2009]. Apart from forestry applications, this work is about gradual deterioration and maintenance of capital investments. All equipment, machinery and vehicles experience wear and tear over time. The cost of operation and maintenance are bound to increase with degradation. At some stage, the maintenance cost may eclipse the difference between the salvage value and purchasing a replacement. At this point, it is economically optimal to salvage and replace the equipment. This theory has created an entire field of useful life-cycle and maintenance modeling (e.g., Dekker 1996 and Scarf 1997). A concrete example is fleet optimization where the cost to maintain a vehicle increases with time since last maintenance. At some point, the cost of maintaining the vehicle is greater than the cost to purchase a new vehicle. This concern is analogous to roads in the EFCM.

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1.7 Appendix I: Model II Formulation

Model II Formulation

$$\text{Max} \sum_{l=1}^{|T|} \sum_{k=-M}^{l-Z} \sum_{m} A_m \rho_{m,k,l} W_{m,k,l} \qquad (A1)$$

$$N_{m,k} + \sum_{l=1}^{|T|} W_{m,k,l} = a_{m.k} \qquad \forall m, k = -M, \dots, 0 \qquad (A2)$$

$$N_{m,k} + \sum_{l=k+Z}^{|T|} W_{m,k,l} = \sum_{t=-M}^{k-Z} W_{m,t,k} \qquad \forall m, k = 1, \dots, |T| \qquad (\text{A3})$$

$$\sum_{m} \sum_{k=-M}^{l-z} v_{m,k,l} W_{m,k,l} = H_l \qquad \forall l = 1, \dots, |T| \qquad (A4)$$

$$1.25H_t \geq H_{t+1} \qquad \forall\, t = 1, \dots, |T| - 1 \qquad (A5)$$

$$.75H_t \leq H_{t+1} \qquad \forall t = 1, \dots, |T| - 1 \qquad (A6)$$

$$\sum_m \sum_{t=-M}^{|T|} Age_t N_{m,t} A_m \geq \sum_m \sum_{t=-M}^{-1} Age_t a_{m,t}\, A_m \qquad (A7)$$

where the parameters are:

A_m = the area of FMU m in hectares;

$a_{m,t}$ = percent of FMU m that is in age class t in period 1 (initial age);

Z = minimum rotation age in periods;

v_{m,t_1,t_2} = volume/ha in FMU m for harvests of age class $(t_2 - t_1)$;

M = the largest age class in the initial inventory;

ρ_{m,t_1,t_2} =revenue/ha in FMU m for harvests of age class $(t_2 - t_1)$;

Age_t = The age of an FMU in time t;

and the decision variables are:

W_{m,t_1,t_2} =The percent of FMU m regenerated in period t_1 and harvested in period t_2;

$N_{m,t}$ =The percent of FMU m in time t that is not harvested.

Objective function (A1) maximizes net present revenue across all FMUs and time periods. Inequality (A2) is the first entry constraint. It makes sure that all of FMU m is accounted for, either as harvested, or not harvested. Decision variables are included in this constraint only if the age classes of the units satisfy the minimum rotation age. The first entry constraint initializes the network flow in Model II. Inequalities (A3) are the network flow constraints that map the possible combinations of subsequent rotations for each time period and FMU. Again, decision variables are included in these constraints only if the age classes satisfy the minimum rotation age. Inequality (A4) is harvest accounting constraints that sum up the harvest volumes for each period and store the value in accounting variable H_t. Inequalities (A5-A6) are harvest flow constraints that restrict the amount of harvest in any one period to be within 25% of the volume harvested in the previous period. Finally, Inequality (A7) is the average ending age constraint that requires that the area weighted average age class in period $|T|$ is at least as large as the area weighted average age class of the initial inventory.

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Chapter 2: A Model Framework for Managing Edge Effects in Harvest Scheduling Using Spatial Optimization

2.1 Summary

Actively managed forest stands can create new forest edges. If left unchecked over time and across space, forest operations such as clear-cuts can create complex networks of forest edges. Newly created edges alter the landscape and can affect many environmental factors. These altered environmental factors have a variety of impacts on forest growth and structure and can alter harvest yields and habitat for wildlife. For example, chances of wind-throw and regeneration shading can increase, which in turn can reduce the expected yield of merchantable timber. Additionally, forest edges can compromise interior forest habitat for wildlife and expose sensitive species to harmful processes such as nest predation or parasitism. We introduce a novel harvest scheduling model that can keep track of and control the spatiotemporal development of forest edges. This allows the forest resource analyst to put constraints on edge production in an attempt to meet a variety of production and sustainability objectives. To demonstrate the model's functionality and tractability, we apply it to a case study in the Pacific Northwest region of the United States.

2.2 Introduction

Forest edges are abrupt changes in stand characteristics such as tree height, stem density, or species composition. Forest edges occur naturally for a variety of reasons, including environmental limits to plant species distributions such as altitude and moisture, or large-scale disturbances such as floods or landslides. Forest management practices can also contribute to edge development. Whether by altering stem density via thinning, or by changing species composition via replanting or habitat restoration, or by altering fuel loads for fire control, management actions can result in a complex network of edges.

Newly created edges alter the landscape and can have a variety of ecological repercussions. We can minimize the negative impacts, while promoting the beneficial ones by giving explicit and careful consideration to edge development in forest planning. However, determining the optimal spatial and temporal layout of management actions is a very complicated task. In this chapter, we propose a spatial optimization model that accounts for individual edges. To illustrate the model in as simplistic terms as possible, we describe a case study where clear-cut forest harvesting is the sole management tool. Although the framework is broadly applicable to a variety of systems and management practices, clear-cut harvests serve as the most intuitive and illustrative example of how forest edges can develop in response to human interventions. Clear-cuts are also advantageous for demonstration purposes because edge effects associated with clear-cuts have been well researched (Chen & Franklin 1992; Chen, et al. 1995; Mitchell, et al. 2001; Burton 2002; Kalcounis-Rueppell, et al. 2010; Irwin, et al. 2013).

Before describing the mechanics of the model, we summarize the physical and ecological effects of forest edges that can result from clear-cut harvesting. We introduce our proposed modeling framework next. To demonstrate the functionality and tractability of the model, we present a case study in the Pacific Northwest United States. Finally, we discuss the model's limitations and broader applications.

2.2.1 Forest Edge Effects

When a forest stand is harvested using a patch- or clear-cut approach, it can create a new forest edge along any or all of the adjacent stands. In this case, the environmental changes on the exterior (cut side) of the edge are obvious. However, the new edge also affects the interior (forest side) of the edge. In general, newly created edges can alter the landscape in many different ways. Chen et al., (1995) investigated how climatic factors change along interior clear-cut edge in the Pacific Northwest. They found significant differences in air temperature, soil temperature, wind speed, short wave radiation, humidity, and soil moisture. These differences extended between 60-240 meters into the forest depending on the specific variable. The altered environmental factors can affect forest growth and structure including merchantable harvest yields and habitat for wildlife. In the following, we discuss these effects in detail starting with the effects on forest growth and structure.

Edge Effects on Forest Growth and Structure

The two biggest environmental factors affecting forest growth and structure due to new edges are increased or reduced sun exposure and increased risk of wind damage. Increased sun exposure (Figure 1A) provides extra short wave radiation, induces higher temperatures and reduces humidity and soil moisture. In certain conditions, this extra exposure increases growth rate. Chen and Franklin (1992) found an increase in relative growth rate (RGR) for Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) near clear-cut edge. However, the increased sun exposure is not always beneficial to tree growth. As an example, Burton (2002) looked at edge effects in boreal Canada and found a decrease in radial incremental growth for Lodgepole pine (*Pinus contorta*) growing near south facing edges. The increase in exposure can reduce humidity as well as available soil moisture. Although these effects may not be sufficient to compromise the growth of mature pines, they can harm mycorrhizae fungi and rhizosphere bacteria, both of whose health and integrity are indirectly tied to the growth of pines (Amaranthus et al., 1993).

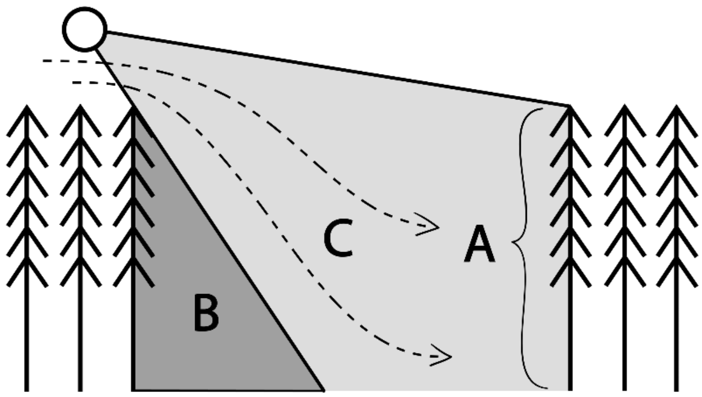

Figure 2-1: Possible physical effects of clear-cut edge. This figure demonstrates three possible edge effects: Increased sun exposure (A), shading of regenerating growth (B), and increased wind exposure (C).

The other major edge effect on forest growth is increased risk of wind-throw due to exposure (Figure 1C). Both Chen et al. (1992) and Burton (2002) found increased amounts of wind damage along edges. In a census, the British Columbia Ministry of Forests found that 4% of the annual allowable cut was damaged by wind in 1991. This was a volume equivalent to the damage caused by insects and wildfire combined in that year (Mitchel 1995). In another study conducted across six forests in British Columbia (three coastal and three inland), clear-cut edges less than ten years old were analyzed for windthrow damage (Lanquaye-Opoku & Mitchell 2005). The authors found that the average loss of 25m-by-25m edge components seriously damaged by wind varied between 4-24% depending on study site. Using regression analysis, they were able to relate the proportion of wind-thrown components to various edge specific parameters such as elevation, slope, and aspect. These results corroborated Burton et al.'s (2002) earlier results about the effects of edge orientation on the amount of wind-throw. In conclusion, these findings demonstrate that not all edges are equal and that individual edges can have very different effects on forest growth.

Edge Effects on Wildlife Habitat

The effects of forest edges are not limited to tree growth. Wildlife habitat can also be impacted (Kimmins 2004). Some species benefit from while others are harmed by forest edges. Large mammals often browse along forest edges where understory plants are abundant, but at the same time, the safety of a dense forest is not far away. Similarly, some predators take advantage of forest edges to remain in cover while they stalk prey in the openings. For example, the northern spotted owl (*Strix occidentalis caurina*) hunts in old growth forests along edges where there is significantly less groundcover for their prey to hide (Irwin, et al. 2013). Another example of wildlife that benefit from edges is bats that harness changing air currents along clear-cuts to for the purposes of more effective aerial predation of insects (Kalcounis-Rueppell, et al. 2010). Conversely, forest edges can also compromise the well-being of some animal species. The marbled murrelet (*Brachyramphus marmoratus*) for instance, faces higher rates of nest predation by *Corvids* near forest edges (Malt & Lank 2009).

In a broader sense, edges affect habitat connectivity and fragmentation, which can, in turn, compromise overall habitat suitability. However, connected habitat for one species may be fragmented from the perspective of another species. The example of moose (*Alces alces*) vs. flying squirrels (*Pteromys Volans*) is case in point. Although moose do not directly benefit from forest edges, edges between a recent harvest and a mature stand can satisfy both of its critical habitat requirements. That is because moose forage in openings and recent clear-cuts where understory plants are plentiful. At the same time, they seek cover and shelter in mature forests. For this reason, edge development can be used as a proxy for moose habitat (Kurttila, et al. 2002). However, while moose benefit from landscapes rich in edges, from the flying squirrel's perspective, the very same landscape might prove to be too fragmented. That is because large openings are an impediment to the flying squirrels' ability to glide efficiently through the canopy from tree to tree in short distances. This is why minimizing edge development to create large contiguous forest patches would be good for this particular species (Kurttila, et al. 2002).

In sum, the spatial and temporal layout of edge generation that is driven by the layout of management actions can have complex repercussions. Many species that inhabit forestlands are considered protected species or provide critical ecosystem services. Both the marbled murrelet and the northern spotted owl are currently listed as threatened species in the United States (Federal Register 2011; Federal Register 2012). Because of this, forest managers must be careful to consider the impacts of harvest scheduling decisions on edge development.

2.2.2 Optimal Management Plans

The spatial layout of management actions over a large area can lead to a combinatorial explosion of potential options to consider. By adding the temporal dimension, the permutations of a sequence of management actions must each be considered separately, which leads to an even greater number of possible alternatives. For example, choosing a sequence of 10 forest management units for some silvicultural treatment out of 100 represents more than 62 quintillion (10^{18}) possibilities. Additionally, these management alternatives must often meet various constraints and limitations. The sheer quantity of options quickly pushes these problems out of the realm of "eyeballing" a good, or even feasible solution.

One way to plan and schedule complex management tasks is to use spatial optimization models. These models optimize the spatial and temporal layout of management actions across a landscape over a finite planning horizon. Examples of spatial optimization applications to forest ecosystem management include habitat reserve selection (Haight & Travis 2008), fuel treatments (Wei, et al. 2008), and harvest scheduling (Tóth & McDill 2009). Harvest scheduling models optimize one or more management objectives (e.g., maximize revenues or harvest volume) over a set of planning periods while meeting a variety of financial and ecological constraints. The concept of edge effect requires knowing which units are adjacent to another, and is therefore inherently spatial. Spatial optimization models typically require binary decision variables that indicate which units to select for a particular management action. For harvest scheduling, this often translates to units being either cut or not. This is required to ensure the spatial integrity of the model; if a fraction of a unit is harvested, there is no way of knowing the amount or location of the resulting edge. By assuming the units can only be clear-cut, we can define possible edges a priori and incorporate edge-specific data into the model.

Optimal land acquisition and reserve design models were the first to incorporate edge effects via spatial optimization. These models tried to minimize the length of exterior edges relative to reserve or land area to promote compact site selection (Wright, et al., 1983; Fischer & Church, 2003). The total edge projected to be present at the end of a given planning horizon was also used for similar purposes in forest harvest scheduling models: as a measure of compactness or habitat fragmentation (Tóth & McDill 2009). A common shortcoming of these models is that they treated all edges equally regardless of edge orientation, aspect or lifespan. Burton 2002 and Scott & Mitchell 2005 have shown that the orientation and aspect of edges can have dramatic impacts on exactly how edges would affect the silvicultural characteristics of adjacent forest stands. By lumping all edges together regardless of their individual characteristics, one can end up discounting or exaggerating their actual impact on habitat or yield. Moreover, individual forest edges arise and fade away dynamically in response to various silvicultural activities as well as to the growth and maturation of neighboring stands. One common boundary shared by two stands can be an abrupt edge during one period of time (e.g., one forest stand is harvested next to another one with forest cover) while the very same boundary could quickly cease to serve as an edge in a subsequent period (e.g., if the other stand is also harvested). Ignoring these "transitory" edges by focusing only on the minimization of the maximum length of edges between mature forest patches and all other stands over the planning horizon (as in Tóth & McDill 2009) can again lead to biased estimations of their true, dynamic impact on wildlife and timber yield.

Example of Varied Edge Development

For this example, the management goal is to treat eight of sixteen identical square units arranged into a four-by-four square (Figure 2) over two planning periods. We assume only four units can be treated in each planning period. Further, we assume edge to form between any treated and untreated units. We consider three models: model A ignores edge production, model B minimizes the number of edges that exist at the end of the planning horizon ($\text{Min.}\, E_T$), and model C minimizes the number of edges produced in each planning period ($\text{Min.}\, E_1 + E_2$). Figure 2 shows the spatial and temporal arrangement of treatments for valid optimal solutions for each model.

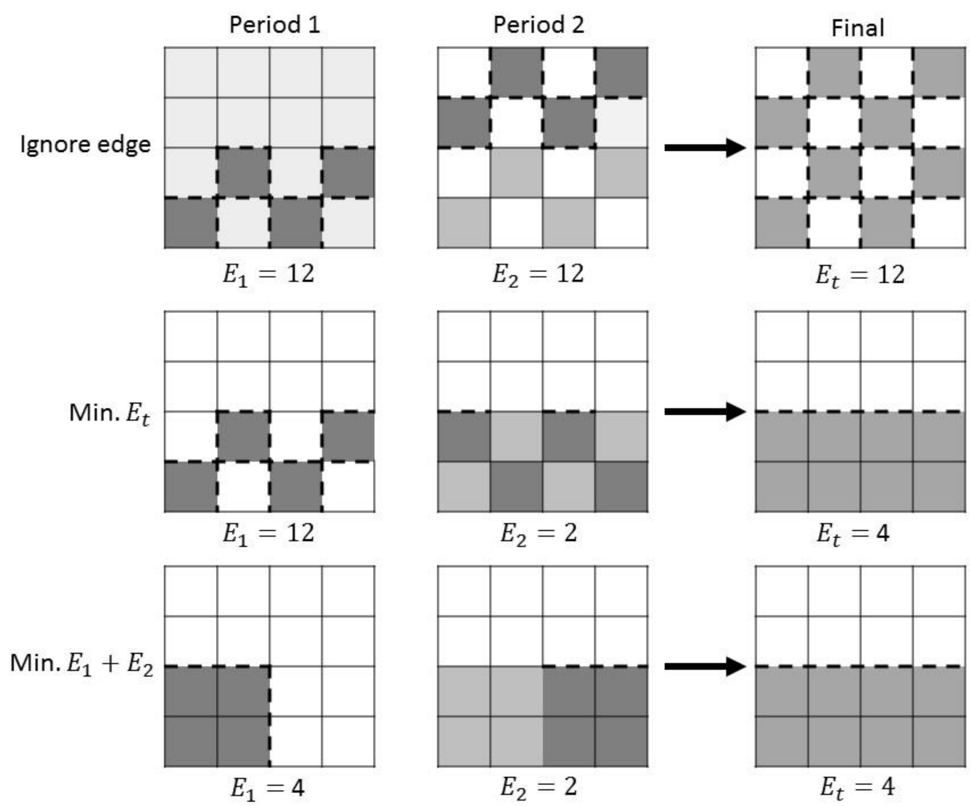

Figure 2-2: Comparison of possible edge production over two planning periods across three models of managing edge.

If we ignore edge production, there is a possibility of extreme behavior. Since all units are identical, any plan that treats eight units meets our management objective, including the solution shown in figure 2a.

This plan creates twelve units of edge in period one and twelve units of edge in period two, leaving twenty-four units of edge at the end of the planning horizon. By minimizing E_T, we guarantee that only four units of edge will exist at the end of the planning horizon. However, this can still create large amounts of transitory edge as is illustrated by the valid solution shown in figure 2b. In period one, the same four units are selected as in the model that ignores edge, and 12 units of edge are created. In period two, the gaps are filled in and only two new pieces of edge are produced, while ten others are eliminated. Even though only four edges exist at the end of planning horizon (the minimum amount), fourteen instances of edges were created over the two planning periods $(E_1 + E_2)$. By minimizing edge produced in each period, we not only minimize the edge left over at the end of planning horizon, but also the transitory edge created along the way. The solution shown in figure 2c only produces six instances of edge over both planning periods, less than half of the overall edge produced by the model B solution, and a quarter of that produced by the model A solution. This example demonstrates that identical management goals can produce widely different temporal and spatial patterns of edge generation. It also demonstrates that to fully control edge generation, we need to be able to consider edge produced in each period, not just the edge that persists after the end of the planning horizon

The model we propose overcomes these shotcomings by accounting for each edge individually between pairs of adjacent forest stands. The proposed model has separate indicator variables for every single shared boundary between stands that switch on and off in response to the silvicultural actions scheduled to occur on those stands. This level of granuality allows one to capture the dynamic feedback between these transitory edges and the projected stand yields or wildlife habitat. Moreover, our new construct also makes it possible to model the directionality of individual edge effects over time. The presence of an edge affects the forest stands or reserve sites in drastically different ways depending on which side of the edge one is looking at. As an example, the effect of windthrow on yield occurs only on the intact, forested side of the edge and not on the side that had been clear-cut. The model we propose accounts for this directionality with a novel mathematical programming construct. We are not aware of any other documented optimization model that can capture all of these key components of edge effects whether they arise in forest harvest scheduling or in reserve selection. The closest others have gotten in utilizing the pair-wise relations of adjacent forest stands have done that done in the context of spatially explicit harvest scheduling models with maximum harvest opening size restrictions (e.g., Snyder & Revelle 1997, McDill et al 2002). In these models, edges have been modeled to represent adjacency between units. This information allows managers to place constraints on adjacent harvest activities, thereby limiting the size of contiguous harvest openings. In our proposed model on the other hand, harvest activities in adjacent stands are coordinated in an attempt to control the negative or positive effects of edges. We present an optimization modeling framework that keeps track of the length, orientation, aspect and directionality of each edge in each planning period. This allows us to model the various forms of edge effects, from wind-throw to altered sun exposure, separately for each edge. Our framework tracks and identifies edges created in all planning periods, and can explicitly account for transitory edges that are not necessarily present at the end of the planning horizon. We discuss how the framework can be used in various management situations and demonstrate its functionality and tractability in a case study in the Pacific Northwest United States.

2.3 Modeling Framework

The proposed model is a mixed integer program (MIP). The MIP optimizes the spatial and temporal layout of management actions, such as harvests, thinning or habitat restoration across a set of management units or reserve sites within a time horizon of, say, $|T|$ time-periods in pursuit of an objective function that represents the primary management or conservation objective:

$$\text{Max} \sum_{i,t} F(x_{i,t}) \qquad (1).$$

Here, $x_{i,t}$ is the binary decision variable that represents whether a given forest treatment should be applied to unit i during planning period t ($x_{i,t} = 1$) or not ($x_{i,t} = 0$). Function F is some linear function of these decision variables that relates the management actions (e.g., harvest or restoration actions) to overall management objectives (e.g., timber revenue maximization). The model optimizes this function while meeting a bevy of additional constraints.

As a concrete example, consider the task of scheduling forest clear-cuts to maximize timber revenues or harvest volumes. In this case, $x_{i,t}$ denotes the decision whether to clear-cut unit i in period t, or not. Our objective function takes the form of

$$\text{Max} \sum_{i,t} v_{it} x_{it} \qquad (2),$$

where v_{it} is the net discounted timber revenue associated with harvesting FMU i in period t. Objective function (2) attempts to maximize the revenues over all time-periods while meeting various sustainability and logistical restrictions including

$$\sum_{t=0}^{|T|} x_{it} = 1 \qquad \forall i \in V \qquad (3)$$

where V is the set of all management units i. Constraint set (3) forces each unit to have only one treatment regime associated with it. In our case, this means each forest management unit (FMU) can only be harvested at most once.

2.3.1 Edge Identification

The key component of the modeling framework is the ability to detect and flag each possible edge in every planning period. To define and flag individual edges, the model compares adjacent units under all possible management scenarios using a *condition* table (a_{itp}). The table shows the "condition" of stand i in each period p under each possible management scenario t. The term "condition" refers to the specific parameter used to define edge in the context of the management problem at hand. For example, stand height, age, or species composition could all serve as "conditions" for the purpose of determining whether an edge exists between two adjacent units in a particular period of time.

To determine the presence of edges, the model compares the values of a_{itp} between all adjacent units in all time-periods. If in any period the difference between a_{itp} values for two adjacent units is greater than a prescribed threshold, the model concludes that there is a directed edge between the units in that time-period. Mathematically,

$$\sum_{t=0}^{|T|}\left(a_{itp}x_{it} - a_{jtp}x_{jt}\right) \leq d_{ij} + Mz_{ijp} \qquad \forall[i,j] \in E, p \in T \qquad (4),$$

$$\sum_{t=0}^{|T|}\left(a_{itp}x_{it} - a_{jtp}x_{jt}\right) \geq d_{ij} - M\left(1 - z_{ijp}\right) \qquad \forall[i,j] \in E, p \in T \qquad (5),$$

where $z_{ijp} = 1$ if the model determines that there is an edge effect on unit i directed through the edge from unit *j* in period p, and 0 otherwise, $E =$ the set of all adjacent units $[i,j]$ in the forest, $d_{ij} =$ the difference in a_{itp} values required to trigger an edge effect on unit i from unit j, and $M =$ an arbitrarily large number, which is at least as much as the largest possible difference in a_{itp}'s. Constraint sets (4) and (5) control the binary indicator variable z_{ijp} in charge of flagging edge effects from unit *j* to *i* in period t. If in any period p, the a_{itp} value for unit i is greater than the a_{jtp} value for adjacent unit j by at least d_{ij}, then z_{ijp} is forced to be equal to 1. If the difference is less than threshold d_{ij}, then z_{ijp} is forced to be equal to 0. Note that edge effects are directional in our proposed model and therefore $z_{ijp} \neq z_{jip}$. Moreover, the constraints prevent z_{ijp} and z_{jip} from both taking the value of 1 in the same period.

With these two constraints, we create a binary indicator variable that tracks the presence of edge created by the management plan. We can then use these variables to set constraints on edge production and directly manage edge effects.

2.3.2 Incorporating Edge into Management Goals

By controlling edge development in the optimization model, we can represent a variety of possible management objectives mathematically. A few brief illustrative examples that demonstrate this flexibility of the model are as follows.

Modeling total edge to account for bat or moose habitat: One of the most basic capabilities of this modeling framework is to track the total length of edges in each time-period as well as over the entire planning horizon:

$$\sum_{[i,j]\in E} z_{ijp} b_{ij} = C_p \qquad \forall p \in T \tag{6}$$

Constraint set (6) is an accounting constraint that sums the total length of edge created in each period. Here b_{ij} is the length of the boundary between units i and j, and C_p is the total length of edge in period p. By comparing the total edge development due to harvest activities under different management scenarios we can examine the trade-offs of providing additional edge for those species that broadly benefit from it. For example, the model allows one to look at the cost trade-off for providing additional edge for bats that benefit from turbulent air conditions at and around forest edges for aerial predation (Kalcounis-Rueppell, et al. 2010).

Similarly, using this modeling framework, one can set a minimum amount of edge between harvested and mature forests (C_{min}) to be present in all periods,

$$\sum_{[i,j]\in E} z_{ijp} b_{ij} \geq C_{min} \qquad \forall p \in T \qquad (7),$$

as a proxy for having available moose habitat.

Modeling edges with specific attributes for northern spotted owl and marbled murrelet habitat: Apart from accounting for total edge development in each planning period, our proposed modeling framework can also account for each specific edge individually. For example, the northern spotted owl often hunts on the forest side of edges between recent clear-cuts and old growth stands (Irwin, et al. 2013). Our model can be used to require an edge to be present within a certain distance of each owl reserve in each time-period,

$$\sum_{i \in A_R} z_{iRp} \geq 1 \qquad \forall\, R, p \in T \qquad (8).$$

Constraint set (8) requires that at least one edge occurs within a certain distance of each owl reserve during each time-period. Here R is a forest management unit marked as an owl reserve, and A_R is the set of units that have borders within a certain distance from reserve unit R. Conversely, marbled murrelets face higher rates of nest predation near edges (Malt & Lank 2009), so one may want to limit the amount of edge within a certain distance from marbled murrelet reserves:

$$\sum_{i \in A_R} z_{iRp} b_{ij} \leq C_R \qquad \forall\, R, p \in T \qquad (9)$$

Constraint set (9) limits the total length of edge near marbled murrelet reserves. Here, R is a unit marked as a marbled murrelet reserve, as well as its surrounding buffers where logging is prohibited, and C_R is the maximum amount of edge allowed on these units plus their buffers in each time-period.

Modeling the feedback between management objectives and increased exposure due to edges: Using our proposed model framework, one can also associate a cost or revenue with each edge being produced. For example, harvested volumes can be adjusted to capture increased sun exposure or windthrow due to newly created edges between specific pairs of adjacent stands.

For simplicity, we assume for this example that edge effects arising in multiple periods are additive in their impact on yield or habitat (this assumption can be relaxed):

$$f_{it} = 1 + \sum_{p<t, j \in A_i} z_{ijp} G_{ij} \qquad \forall i \in V, t > 1 \in T \tag{10}$$

$$y_{it} \leq N x_{it} \qquad \forall i \in V, t \in T \tag{11}$$

$$y_{it} \leq f_{it} \qquad \forall i \in V, t \in T \tag{12}$$

$$f_{it} - y_{it} \leq N(1 - x_{it}) \qquad \forall i \in V, y \in T \tag{13}$$

$$\text{Max} \sum_{i,t} v_{it} y_{it} \tag{14}$$

Constraint set (10) defines the value of yield adjustment factor f_{it} for unit i harvested in period t, by adding all edge effect adjustments that are projected to occur prior to period t. Here f_{it} denotes the percentage of total volume lost in unit i by period t. Parameter set G_{ij} represents the individual yield adjustments for unit i in only one planning period via its shared edge with unit j. Set A_i denotes all the units adjacent to unit i. In Constraint set (10), we only sum over $p < t$ because edges that arise post-harvest can no longer alter the already harvested yields. Lastly, there is no yield adjustment in the first period of the planning horizon due edges that might have developed in the past. For simplicity, we assumed that the data on current yields already captured past edge effects.

Constraint sets (11-13) linearize the product of the binary harvest variable x_{it} and the continuous adjustment variable f_{it} . Here N is an arbitrarily large number at least as large as the largest possible total adjustment. Variable y_{it} represents the product $x_{it}f_{it}$. As a last step, we replace Objective Function (1) with (14) using the adjusted harvest variables y_{it}.

Together these constraints create a harvest scheduling model with yields adjusted by the presence or absence of forest edges. The coefficient set G_{ij} can represent a wide variety of edge effects, such as reductions or increases in yield or wildlife habitat, making the model very flexible. Additionally, the temporal dimension of the adjustment factor f_{it} allows the user to account for different responses to edge effects in stands that are of a different age. For example, an older stand might respond differently to wind or nest predation than a younger one, everything else being equal. In the next section, we will use this set up to demonstrate the functionality of the model in a case study where edge effects reduce overall yield due to wind damage.

2.4 Case Study

2.4.1 Model Configuration

As a proof of concept, we configured our proposed model to adjust harvest yields based on projected wind damage. We set the adjustment factor for wind-throw to represent the percentage of volume lost due to wind-throw events. Based on Lanquaye-Opuku & Mitchell (2005), we assume there is a probability p of wind to damage a 25m by 25m segment of forest edge. To calculate this probability for each individual shared boundary between adjacent units, one can take a wide variety of factors into account such as aspect, slope, and soil type. We defined Function G_{ij} as:

$$G_{ij} = -\left(\frac{b_{ij}p}{sl} \times \frac{sl^2}{Area_i}\right) \tag{15}$$

where the shared boundary (b_{ij}) is divided by the segment length (*sl*=25m in this study) to calculate how many segments are found along the boundary between i and j . Then, by multiplying by p we find how many segments were likely to be damaged. From there, we convert the number of damaged segments into a percentage of total area. This value represents the percentage of total area projected to be lost due to windthrow associated with the shared boundary between units *i* and *j*. Although we used uniform windthrow probabilities for this particular case study, programs like WINDfarm (Lanquaye-

Opoku & Mitchell 2005) could be used to estimate probabilities that are more realistic and determined by site-specific factors.

For this case study, our management objective was assumed to maximize harvest yield. Hence v_{it} in the objective function represents the projected volume of stand i in period t. In addition to constraints (3-5) and (10-13) we include two operational constraints commonly applied to harvest scheduling models: harvest flow constraints, and ending age requirements. Inequalities (16) and (17) create the harvest flow constraints:

$$LH_{t-1} \leq H_t \qquad \forall t > 1 \in T \tag{16}$$

$$UH_{t-1} \geq H_t \qquad \forall t > 1 \in T \tag{17}$$

These constraints force the difference in total harvest volume (H_t) between consecutive time-periods to be within a certain range defined by the upper and lower bound parameters *U* and *L*. Inequality (18) is an ending age constraint:

$$\sum_{i} Area_i \left(a_{i01} - \frac{1}{2} l\right) \leq \sum_{i,t} Area_i \left(a_{it10} + \frac{1}{2} l\right) x_{it} \tag{18}$$

where $Area_i =$ the area of management unit i, and $l =$ the length of the planning period. This constraint ensures that the area weighted average age of the units at the end of the planning horizon is greater than or equal to the area weighted average age at the start of the planning horizon.

To demonstrate the value of the proposed model, we compared its performance in terms of lost harvest volumes to that of a control or naïve model that ignored the edge effects in its objective function. However, the control model was still formulated in such a way so that the timber volumes along edges effected by windthrow would still suffer from the same losses as the proposed model. In the control model, the objective function and harvest flow constraints reference the un-adjusted harvest variables x_{it} instead of the y_{it}'s present in the proposed model. This causes the optimization model to assume there is no edge effect feedback on the objective function; although the actual harvest yields are still adjusted based on the appropriate wind-throw probabilities. We used harvest accounting variables in the control model to keep track of total harvest volumes adjusted for windthrow.

2.4.2 Parameterization and Data

The data used in this case study is from the Charles L. Pack Experimental and Demonstration Forest, located 2.3 miles southwest of Eatonville, WA. The 1740 ha forest is divided into 186 stands of varying slopes, aspects, soil types, ages, and species composition. Data used from this forest included stand locations and adjacencies, boundary lengths, and stand ages. Boundary lengths were calculated from polygon layers in a geographical information system (vector data). The data is freely available online through the FMOS database hosted by the University of New Brunswick.

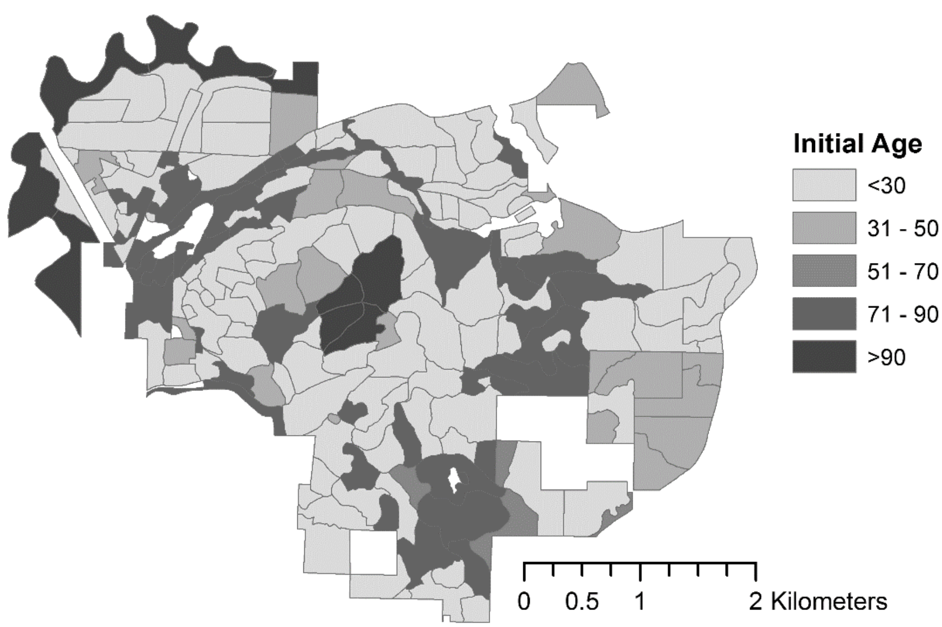

Figure 2-3: Initial age distribution of the Charles L. Pack Experimental and Demonstration Forest.

We ran both the proposed- and the control models under a variety of wind probability scenarios using a planning horizon of 50 years with five 10-year planning periods. The threshold difference in age to trigger edge effects (d_{ij}) was set to 15 years for all pairs of harvest units sharing a common boundary. Maximum percent fluctuations in harvest volumes between adjacent planning periods were set to 25% ($U = 1.25, L = 0.75$). We tested four scenarios with uniform windthrow probabilities of 0%, 5%, 15%, and 25%.

Once formulated, all models were solved using IBM ILOG CPLEX 64-bit 12.6.0 (IBM 2011). We solved the control models to full optimality for all scenarios, while we gave the edge effect model four hours of solution time for each scenario. We used default values for all other CPLEX parameters.

2.4.3 Case Study Results and Discussion

The optimal harvest values for each model under varying probabilities of windthrow are shown in Table 1. For the proposed edge effect model, all runs finished with an optimality gap of less than 2%, but did not achieve full optimality. This means that the results shown in Table 1 could be even more drastic since the proposed model may have a higher optimal objective function value. In all cases, it is clear that our model performs better than the control model that ignores edge effects. For the extreme "heavy wind" scenario where a quarter of every edge blows down, the edge effect model was able to avoid more than half of the volume losses due to wind when compared to the control model. This shows that even in extreme scenarios, the proposed model can alter the spatial and temporal layout of management actions to significantly reduce edge effects on yield.

Probability of windthrow p	Accounting for edge effects	Ignoring edge effects
$p = 0$ (No wind)	116539 (100%)	116539 (100%)
$p = .05$ (light wind)	115429 (99.05%)	114841 (98.54%)
$p = 0.15$ (moderate wind)	114163 (97.96%)	111214 (95.43%)
$p = 0.25$ (heavy wind)	112967 (96.93%)	108412 (93.02%)

Table 2-1: Results from the case study. The table details total volume harvested under a variety of wind probabilities for the edge effect and control models. Numbers in parenthesis represent percent of maximum harvest ($p = 0$).

Figure 3 compares the spatial configurations of harvests for the control and edge effect models under the moderate wind scenario. The maps imply that the proposed model spatially concentrates the clear-cuts to minimize losses in timber volumes due to windthrow (larger contiguous shaded areas). Additionally, the model minimizes edge loss by sequencing harvests, demonstrated by fewer instances of dark grays next to light grays.

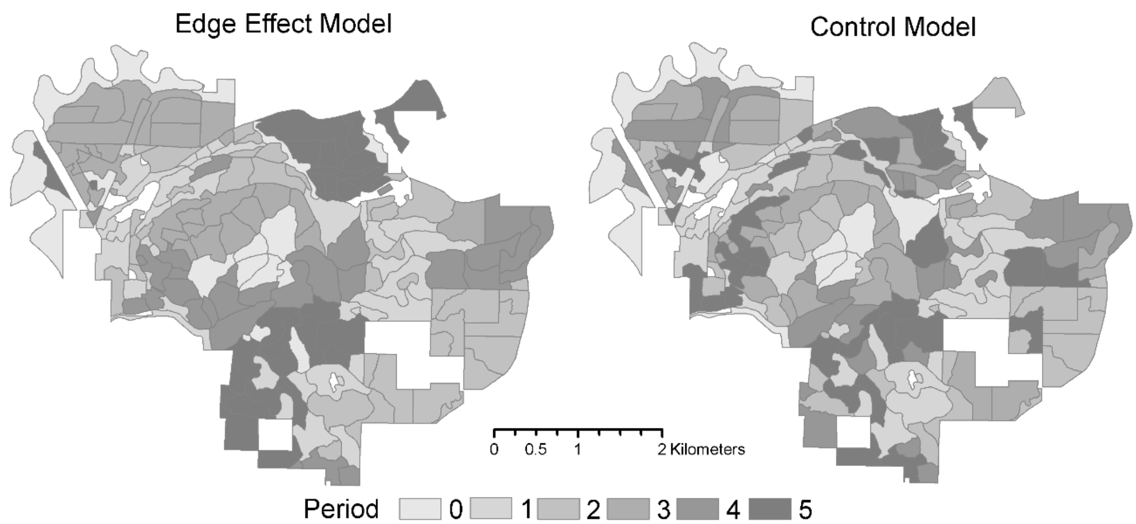

Figure 2-4: Comparison of harvest layouts under the moderate wind scenario. The edge effect model groups harvests together to minimize loss associated with wind throw along edges.

Although many simplifying assumptions were made for this case study, it demonstrates how the proposed model can incorporate the complexity of edge effects on harvest yield at relatively low computational costs. The exact benefit of accounting for windthrow will be location specific, however. Different jurisdictions might have different spatial restrictions on logging and these restrictions can easily interact with constraints on edge development. Of particular importance are the green-up and maximum clear-cut size restrictions. The ability to minimize edge is dependent on the model's freedom to aggregate management actions spatially and temporally. However, green-up and maximum clear-cut size regulations place limitations on the temporal and spatial aggregation of harvests. A number of published models for limiting maximum clear-cut openings are also driven by binary harvest variables (x_{it}). As a result, the two modeling frameworks are compatible and there is nothing that would prevent the analyst from integrating the two.

2.5 Discussion and Conclusion

Management decisions often come with unintended consequences. The spatial and temporal arrangement of forest management actions can produce complex networks of edges. These edges in turn can have a variety of effects on forest growth and yield and on wildlife habitat. In this chapter, we have presented a modeling framework that directly considers the development of edges when creating optimal management plans. To illustrate the general applicability of the proposed model framework, we discussed several potential edge effects that can occur due to logging, as well as the potential management solutions that our model could identify to overcome the negative repercussions of these effects. In a case study, we configured the modeling framework to represent biomass loss due to an increase in windthrow probability due to newly formed edges. Our model outperformed the control model in all instances, generating harvest schedules that minimized the expected damages of wind-throw.

Although we demonstrated the mechanics and the benefits of our model in the context of clear-cut harvesting, it is important to note that edge effects could also arise in the context of other silvicultural activities such as thinning. If such effects were found to be significant, the same mathematical structure can be used in the harvest scheduling models to account for these effects as the one presented here. Thinning-induced edge effects would have to be quantified empirically before they can be incorporated in the harvest scheduling models. While no such empirical data is available today, our proposed modeling framework could be used to address this issue once data availability is no longer an issue.

Beyond forest harvesting, the proposed model can be applied to fuel treatment allocations for wild-fire management, habitat restoration and invasive pest management. The flexibility stems from the way the model determines the presence of edge effects using the condition parameter a_{itp}. In the case study, we defined edge effects based on the difference in stand age between two stands sharing a common boundary (a_{itp}). However, these values can also represent other metrics as well. For fire management, edge could be defined based on the difference in the amount of coarse woody debris or ladder fuels between two adjacent plots. For habitat restoration, edges might be defined based on species composition percentages or a binary comparison of treated vs. untreated units. For invasive species monitoring, we could define edge based on the time since a unit was last monitored or treated. Even within our case study, we could model edge in different ways. For example, since stand growth tapers off beyond a certain age, a difference in age will mean less of a difference in height over time. We could set the a_{itp} values to represent projected tree height, which would more accurately capture the presence or absence of edges as it pertains to windthrow – at the cost of requiring additional knowledge about the system. Similarly, the value of threshold parameter d_{ij} could depend on site-specific information such as dominant species or site class. Even the edge effect adjustment factor G_{ij} could be redefined by converting wind-throw into pulp salvage instead of volume loss.

The applicability of the modeling framework still has its limitations. The main limitation of the model is its reliance on predefined management areas and binary management actions. Both of these assumptions are required to define the exact size, location, and characteristics of possible edges. Because edge effects are highly contextual and can vary with location and orientation, we need information about an edge's exact characteristics to be able to model its effects on the system. Compounding this issue, raster data is often used in natural resources, but does not accurately reflect edge metrics. For example, all edges in a raster are represented with vertical or horizontal lines, which does not accurately represent a curved border. This can cause the length of the edge to be under- or overestimated. Because this can introduce bias into edge metrics, we should exercise special care and caution when quantifying edge metrics using raster-based data. Another limitation is the assumption that harvests occur at the mid-point of planning periods. Under this assumption, the model effectively measures the average amount of edge produced. However, the exact amount will depend on the tactical implementation of the strategic harvest plan.

Lastly, the inclusion of binary variables and constraints that can introduce endogenous feedback can add a significant level of complexity to the optimization model. Depending on the spatial and temporal scope of the management problem, this may be a considerable drawback.

Finally, we emphasize that the management scenarios discussed in this chapter were simplifications used to illustrate possible applications of the modeling framework and did not attempt to capture the true complexity of the underlying systems.

In conclusion, we can help to mitigate the negative effects of edges and provide more ecologically sound management plans by explicitly considering the broader aspects of our management decisions. Edge effects are a wide-ranging phenomenon that can have a variety of impacts. By directly modeling edges within our proposed spatial optimization framework, one can add constraints that control where and when edges might arise on the landscape in an attempt to provide optimal bundles of ecosystem services.

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Chapter 3: Dynamic Forest Harvest and Road Reconstruction Scheduling with Line Graphs

3.1 Summary

Forest roads are an integral and costly component of forest operations. Optimizing road access and harvest decisions independent of each other can lead to inefficiencies and lost revenues. Unfortunately, these joint road access and harvest scheduling problems are quite complex and difficult to solve. The complexity of the network flow models used to determine routing heavily depends on the size and layout of their road network. In this study, we investigate how an alternative network representation, based on the line graph of the network, affects the solution quality of these joint road-access and harvest-scheduling problems. We illustrate the mechanics of the new model on a case study in the Pacific Northwest, and show that it competes with the benchmark formulation in terms of computational performance.

3.2 Introduction

Road access is a critical issue in forestry: to manage a particular location, there must be a safe way to access it. However, the rugged terrain, remote locations, and strict safety and environmental regulations make the construction and maintenance of the forest road networks one of the largest management costs in forestry. Because of this, it is beneficial to consider road access while determining harvest schedules (route-finding). Unfortunately, jointly optimizing road access and harvest scheduling decisions is a very difficult problem. However, one of the main factors that determines the complexity of route-finding is the number of roads and their specific spatial configuration. We propose and test a novel graph theoretical representation of the road network in an attempt to improve the computational performance and the practical usability of integrated harvest and forest road reconstruction scheduling models.

Although road networks have an intuitive traditional spatial representation (TSR) where roads are represented as arcs connecting two points (see Fig.3-1), it may not be the best representation for route-finding. The line graph representation (LGR) of a road network, models the roads as nodes, and uses edges to represent shared intersections. Despite being less intuitive, the LGR creates a more logical graph-model where the objects of interest (the roads) are represented by nodes, and edges represent relationships between the objects. Although both representations accurately model the road network, the resulting graph networks can significantly differ in both size and configuration. Since the constraints and variables that drive route-finding depend on the network's size and connectivity, the choice of network representation will influence a model's solvability.

In this chapter, we test how an alternate network representation affects the solution times of a joint harvest scheduling and road access optimization model. We integrate route-finding by linking a harvest-scheduling model to a network routing model to determine optimal harvest routes. To test the impacts of an alternate network representation, we apply our model using two different representations of a road network: the traditional spatial representation (TSR) where roads are defined as edges between nodes, and the line graph representation (LGR) where roads are modeled as nodes, and edges represent shared intersections.

We begin with a brief review of the joint harvest-scheduling and road-access problem in forestry, route-finding, and line graphs, before providing a formal mathematical description of our proposed Harvest-Scheduling and Route-Finding model (HSRF). This is followed by a case study in the Washington State Department of Natural Resources' (DNR) Olympic Experimental State Forest (OESF), in the United States. Finally, we discuss our results, and their implications for forest managers.

3.2.1 Harvest Scheduling and Road access

The purpose of Harvest-scheduling models is to optimize the spatial and temporal layout of harvest actions across multiple Forest Management Units (FMUs) to best meet management objectives, while satisfying a variety of economic and environmental constraints. To manage a particular FMU, workers must be able to access it in a safe and responsible manner. This requires the construction and or maintenance of forest roads that meet multiple environmental and safety standards. The rugged terrain, remote locations, and strict regulations make the construction and maintenance of the forest road networks one of the highest management costs in forestry. Because of this, there are appreciable benefits to considering road access while determining harvest schedules.

Prior to the mid-1970s, harvest-scheduling models considered road access only indirectly or hierarchically—after the harvest schedule had been determined (Johnson and Scheurman 1977). The connection between road access and harvest location was ignored, leading to inefficiencies and increased costs. Weintraub and Navon's mixed integer programming model (1976) was one of the earliest attempts at jointly optimizing harvest scheduling with road construction and routing decisions. Due to the computational limits at the time and the complexity of the problem, the authors tested their model only on very small, illustrative data sets. The Integrated Resource Planning Model or IRPM (Kirby, et al. 1980) was a much more robust planning tool that integrated the two decisions. To demonstrate the financial savings of integrating road construction decisions with harvest scheduling, Jones et al (1991) compared the IRPM to a hierarchical model that optimized the harvest schedule first, and then optimized the road network second. Using real-world data sets, Jones et al. found that the IRPM's solution was significantly higher in net present value than the decoupled model (up to 43%).

Unfortunately, the majority of the harvest scheduling models that account for road costs or integrate road maintenance decisions (e.g. Weintraub and Navon 1976, Bettinger, Sessions and Johnson 1998) are extensions of the classic Fixed Charge Problem (FCP) of operations research, which has been shown to be NP-Hard (Maniezzo and Paruccini 1998). The difficulty of finding optimal solutions to these integrated harvest scheduling models forced researchers in the past to simplify the problem (for example, only including routing in particular locations or planning periods), and turn to heuristic solution techniques. These included simulation (Weintraub and Cholary 1991), the interchange method (Murray and Church 1995), simulated annealing (Chung and Sessions 2003, Murray and Church 1995), Tabu search (Richards and Gunn 2000, Murray and Church 1995, Bettinger, Sessions and Johnson 1998), ant colony optimization (Contreras, Chung and Jones 2008), heuristic integer programming (Weintraub, et al. 1994), and the great deluge method (Chung and Sessions 2001).

3.2.2 Route-Finding

The goal of route-finding is to find the set of road segments that connect all harvested FMUs from their access points to the road network (sources) to the exit points for the network (sinks) for the lowest combined cost. The set of segments that connect an FMU's source to a network sink are referred to as the FMU's hauling route, or path. The necessity and benefits of route-finding depend on the road network. If there is only one way through the network for a harvested FMU to reach a sink, then the problem is simplified since it is possible to predefine the optimal route for the FMU instead of finding the route each time it is needed. However, if there is more than one way to travel through the network, a predefined static route may not be the optimal choice despite it being the least cost path for a specific FMU to a specific sink.

A crucial component of route-finding is that it determines road access and routing decisions considering the needs of the entire system. Forest road reconstruction and maintenance are generally regarded as "fixed costs" that do not fluctuate with the amount of use or time. This allows route-finding to take advantage of the fixed cost structure by considering the cost reduction afforded by shifting individual routes to overlap, and thereby reducing the total fixed costs associated with forest road maintenance and reconstruction. Figure (1) illustrates a schematic example of how static routes can fail to take advantage of fixed cost savings. For simplicity, suppose that in this example using fewer road segments to access the FMUs will incur less fixed road maintenance costs. The predefined least cost paths for both FMUs is shown in bold in Fig. 1a. These are the paths that require the fewest segments to connect the FMU to the facility. However, if both FMUS are scheduled for harvest, then a better solution exists (Fig. 1b).

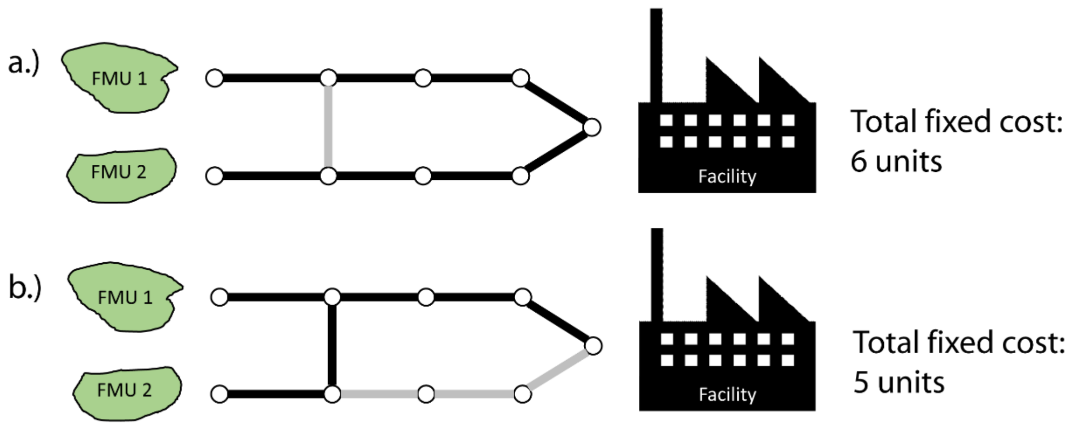

Figure 3-1: Coordinated harvest and road access scheduling can reduce fixed costs. Panel (a) shows the predefined least cost hauling routes for each FMU in bold (six segments). Panel (b) demonstrates a better solution if both FMUs can be harvested in the same planning period (five segments). Note: Each road segment incurs the same fixed cost for reconstruction.

To take advantage of fixed cost savings, the hauling route for FMU 2 shifts to overlap with the route used by FMU 1. Although this highly simplified example only saves one road segment's worth of reconstruction, with many FMUs and a large network, there is the possibility for large savings. In the worst case scenario, all FMU's are routed using their predefined shortest paths, and the solution is identical to using predefined routes.

Beyond more efficient routing of harvested FMUs, route-finding includes other benefits. Crucially, it eliminates the need to preprocess the road network to define routes. This allows the model to be used to investigate and explore changes in the road network, and to test possible what-if scenarios. For example, analysts can test the effects of removing or adding a road segments to the network, or determine what roads are likely to be used within the first several planning periods. The trade-off for these benefits is the added modeling complexity. Because these problems remain difficult to solve and depend on the specific network configuration, it is valuable to consider how the underlying road network's representation can affect overall solution behavior.

3.2.3 Line Graphs

Line graphs result from a transformation applied to a network that potentially alters the number of arcs, nodes, and their specific connections (Krausz, 1943). In addition to the traditional spatial representation (TSR) of a road network where roads are depicted as edges, and intersections are represented by vertices (like on a map), we also consider routing on the line graph of the traditional network. For the line graph representation (LGR), each road segment is represented by a vertex, and an edge represents a shared intersection between two roads, indicating that vehicles can travel (or flow) from one road segment to the other road segment as determined by the original road network (Fig. 2):

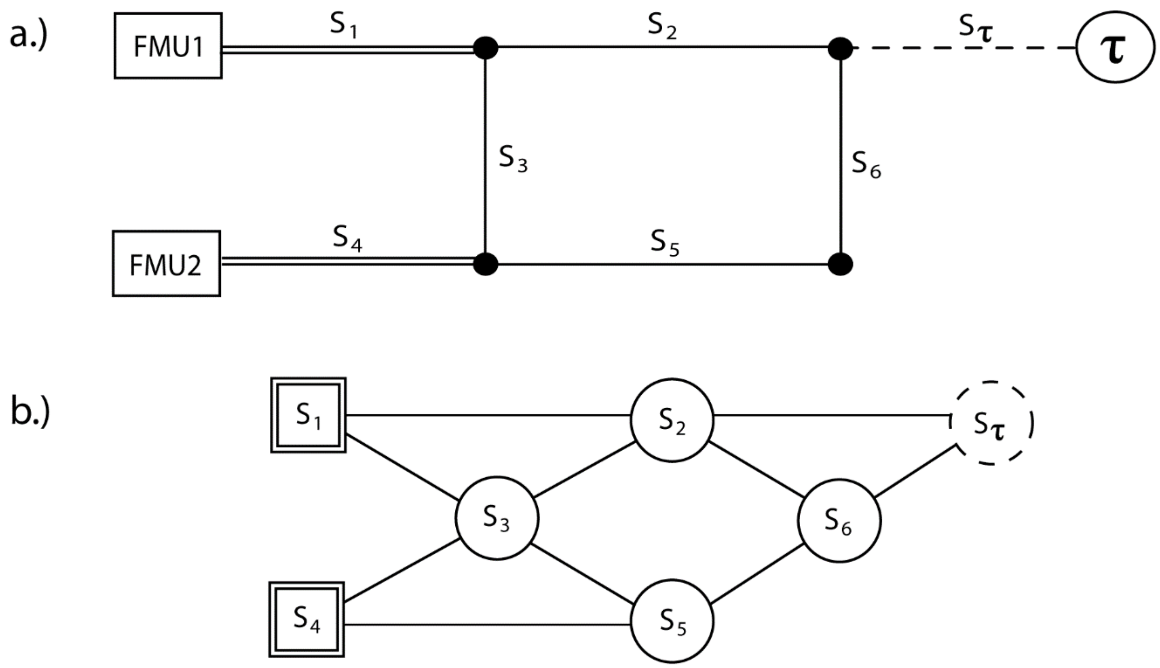

Figure 3-2: Line graph of a simple road network. The traditional road network above (a) is transformed into the line graph network (b), where road segments ($\mathrm{S}_1, \mathrm{S}_2$…) are represented as vertices, and their intersections as edges. Segments S_1, and S_2 are sources and S_τ is a sink.

Although this representation is counter-intuitive, it allows for a more consistent and logical graph model where the entity of interest (the road) is represented by a node and the edges represent a relationship between entities (here, a shared intersection). Several previous studies have found benefits from considering the LGR including work on the aircraft rotation problem (Clarke et al. 1997), the cache location problem in networking (Krishnan et al 2000), and partition problems (Evans and Lambiotte 2009).

In the line graph, each road segment is represented as a single feature regardless of the direction of flow on it: S_i. In contrast, traditional graph representations of transportation networks (e.g., ESRI's Network Analyst) define road segments by its end points *a* and *b*. This results in two representations of the same segment $S_{(a,b)} = S_{(b,a)}$. It also allows an unequivocal determination of hauling routes from each FMU that is scheduled to be cut in a given planning period. Figure 3 illustrates why this is the case. It is not clear in the traditional graph, where segments are represented as edges and intersections as nodes (Fig. 3a), which of the three input flows is routed to Segment S_4. The only information available is that one unit of flow is on Segment S_4. In contrast, the line graph of the same network (Fig. 3b) leaves no ambiguity that it is the flow from Segment S_3 that is routed to Segment S_4, while the flows from Segments S_1 and S_2 go to Segment S_5.

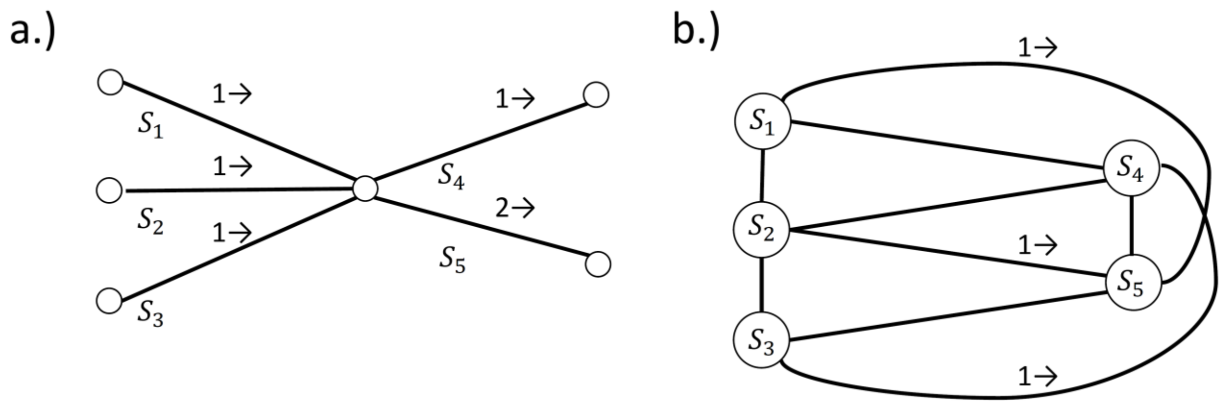

Figure 3-3: Comparison of flows in a traditional (a), vs. the line graph (b) network. The values on the arcs represent flow between nodes. Unlike the conventional network, the line graph approach leaves no ambiguity as to which of the three input flows are routed to Segment S_4.

Figures 2 and 3 also demonstrate that the line graph of a network can alter the number of nodes and edges in the network, as well as their connectivity. Because the constraints that define the network flow model for route-finding depend on the exact size and configuration of the network, this transformation can alter the solution behavior of the problem. To test how this difference in network representation affects solution behavior, we propose a mixed integer model for harvest-scheduling with route-finding, and apply it to a case study using both the traditional and line graph representations of the road network.

3.3 Methods

We propose the Harvest-Scheduling with Route-Finding model (HSRF) to integrate route-finding into an industry standard harvest-scheduling model. The road costs are determined by routing timber intersection-to-intersection on an established road network. The network is assumed to be represented by an undirected graph of vertices and edges. Each FMU is assumed to have at least one access point to the road network, and the formulation allows for multiple exit points from the network.

Using the road network, we construct a network flow optimization model inspired by Conrad et al.'s (2012) habitat connectivity model. Whenever an FMU is harvested, flow is added to the network at the FMU's source node. The model enforces flow conservation (flow into a vertex must always equal flow out of the vertex), which forces all flows to reach a sink. Any road segment that receives any amount of flow contributes its reconstruction cost to the objective function. Because of this, the model seeks to minimize the cost of the network required to route the harvested FMUs.

This model formulation is used for both the traditional and line graph representations of the road network. The difference is what the sets represent. In the traditional representation, the set of vertices (V), represent the intersections between roads, whereas in the line graph, it represents the road segments. Similarly, flow is measured along road segments in the traditional representation, and across intersections in the line graph. A formal mathematical definition of the HSRF follows:

3.3.1 The Harvest-Scheduling with Route-Finding Model (HSRF)

Sets:

$U =$the set of FMUs

$V =$The set of vertices not considered end points (sinks) for the network.

$E =$ The set of edges , defined by starting and ending vertices (i, j)

$N_i =$The set of vertices accessible from vertex i (i.e. $j|(i, j) \in E$).

V_τ =The set of vertices that are considered end points (sinks) for the network.

τ = The "imaginary" vertex that all vertices in V_τ are connected to (the sink)

T = the set of 10-year long planning periods with $t = 1,2, \dots, |T|$. Harvests and road reconstruction activities are assumed to occur in the middle of the planning periods.

Variables:

$x_{m,t} =$ Harvest of unit m in period t.

$F_{(i,j),t}$ =The flow between vertices i and j in period t.

$s_{i,t}$ = The decision to maintain road i in period t.

Parameters:

$\rho_{m,t}$ = the net discounted revenue associated with harvesting FMU m in period t.

A = the total number of cost tiers;

M = an arbitrarily large number $\geq |U|$

d = discount rate. (i.e. .05 for 5%)

pl = length in years of the planning period.

Formulation:

Objective function:

$$\text{Max} \sum_{m,t} \rho_{m,t} x_{m,t} - \sum_{i,t} \phi_a \alpha_i s_{i,t} (1+d)^{\left(\frac{pl}{2} - plt\right)} \tag{1}$$

Subject to:

$$\sum_{i \in N_j} F_{(i,j),t} = \sum_{k \in N_j} F_{(j,k),t} \qquad \forall j \in V, t \tag{2}$$

$$\sum_{i \in V_\tau} F_{(i,\tau),t} = \sum_{m} x_{m,t} \qquad \forall t \qquad (3)$$

$$M \sum_{\phi} s_{i,t} \geq \sum_{i \in N_j} F_{(i,j),t} + F_{(j,i),t} \qquad \forall\, i, t \qquad (4)$$

$$\sum_{j \in N_m} F_{(m,j),t} = x_{m,t} \qquad \forall\, m, t \qquad (5)$$

$$x_{m,t} \in [0,1] \qquad \forall\, m, t \qquad (6)$$

$$s_{i,t} \in [0,1] \qquad \forall\, i, t \qquad (7)$$

The objective function (1) maximizes the discounted net revenues associated with the management of $|U|$ FMUs over a planning horizon of $|T|$ planning periods. The first term accounts for the discounted net harvest revenues, whereas the second term accounts for the road reconstruction costs using a discount rate of d.

Constraint set (2) are the “flow” constraints. These inequalities make sure whatever flow comes into a vertex, must also exit that vertex, except for “sinks”. The first term represents all the flow coming into a vertex from other vertices, while the second term represents the total amount of flow leaving the vertex. Since the sinks are the end points of the network, flow preservation constraints do not apply to them: what flows into a sink stays there.

Constraint set (3) are the “Sink constraints” that make sure all flow is exiting the system, and not stuck in a cycle. The first term represents all the flows that make it to the sink. The second term represents the total amount of harvest in a given planning period. By forcing the two terms to be equal, the constraint ensure that all flow exits the network, and therefore all harvests have an assigned hauling route. Without these constraints, it would be possible for a flow to be stuck in a cycle where what flows out of a vertex, eventually flows back in without ever leaving the system. This situation meets the flow constraints since in-flow equals out-flow, but does not route the flow out of the system. The sink constraints are in place to ensure that all flow will eventually leave the system.

Constraint set (4) are the "cost triggers". These constraints trigger the binary reconstruction variables $(s_{i,t})$ if there is any flow on Segment i. If there is any flow on segment i then at least one reconstruction variable is forced to take the value of one. The large M parameter ensures that the left hand side will always be greater than the right hand side when a reconstruction variable takes the value of 1. The cost triggers are what link routing decisions to the objective function (1).

Constraint set (5) creates the source flow for the system. It forces a unit of flow to enter the system each time a FMU is harvested. By applying a coefficient to the binary harvest indicator x_{it}, the input flow can represent a variety of system specific metrics such as harvested volume, or predicted number of truck passes required.

Finally, constraint sets (6) and (7) declare the decision variables as binary.

3.4 Case study in the Pacific Northwest

To demonstrate the HSRF model and test the alternative network formulations, we applied it to the Olympic Experimental State Forest (OESF) managed by the Washington State Department of Natural Resources (DNR). The case study serves two purposes. First, it demonstrates the practicality of parametrizing the model and integrating it with standard industry work flows. Second, it allows us to test the computational performance of the alternative network formulations in a real world scenario, instead of a hypothetical landscape.

The dataset for the case study was derived from the DNR's Olympic Experimental State Forest (OESF) using Woodstock (Remsoft, 2013), DNR's choice of harvest scheduling software. The case study dataset has an underlying road network of over 25,000 road segments that provide access to over 5,000 FMUs (Figure 4). We used a 100-year planning horizon with ten 10-year long planning periods. The objective was to maximize net present value resulting from timber operations subject to harvest flow and ending age constraints. The HSRF was used to determine timber haul routes and road reconstruction schedules using both the traditional and line graph representations of the road network.

DNR uses Woodstock commercial forest planning software for harvest scheduling. For the case study, we link the HSRF to Woodstock's Model II harvest-scheduling formulation with a set of "trigger" constraints:

$$H_{min}\, x_{m,t} \le \sum_{k=-M}^{k<t-Z} W_{m,k,t} \qquad \forall\, m,t \tag{8}$$

$$H_{max} x_{m,t} \ge \sum_{k=-M}^{k<t-Z} W_{m,k,t} \qquad \forall\, m,t \tag{9}$$

where H_{min}, and H_{max} are the minimum and maximum threshold values to turn on or off $x_{m,t}$ (H_{max} is an upper bound on the areas of the units), and $W_{m,k,t}$ is the continuous harvest variable from Model II. These constraints cause the continuous harvest variables of Woodstock, to switch the binary harvest indicators (x_{it}) in the HSRF on and off. By linking the HSRF to the Woodstock model, whenever an FMU with a valid source is harvested, it must be routed to a sink. If the FMU is not required to be routed, then the HSRF poses no restrictions on that FMU. Once merged, the resulting model is solved with IBM ILOG CPLEX 64-bit 12.6.1 (IBM, 2015) using default settings.

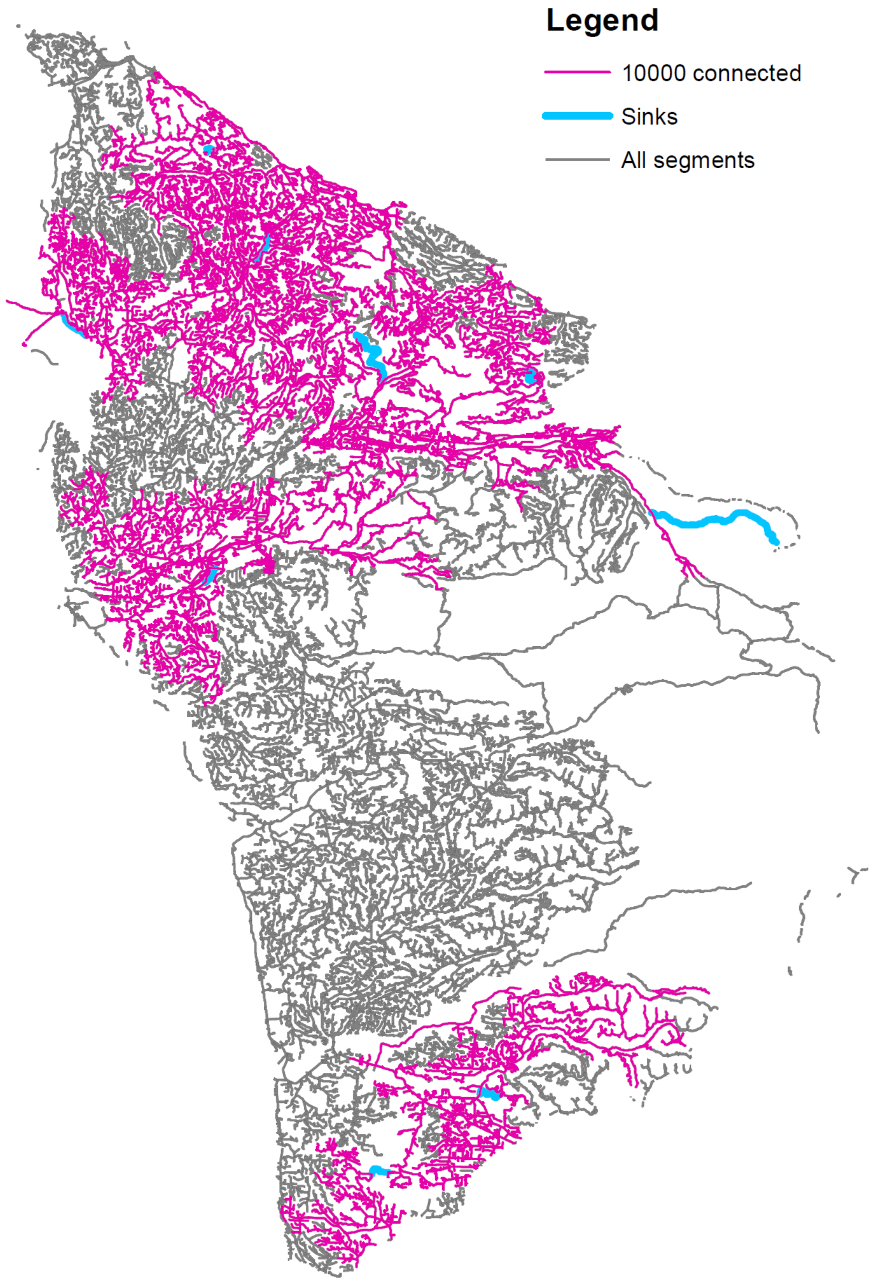

Figure 3-4: The road network for the OESF dataset. As a representation of the road density in the overall area, pink segments show a network of ~10,000 segments connected to the sinks.

3.4.1 Case Study Assumptions and Model Parameterization

The purpose of route-finding is to route harvested FMUs from their source, through the road network, to a sink. However, in our case study dataset we found that it was possible for FMUs to have multiple sources to access the road network, or no established access to, or exit from, the road network. This is great example of the complications that can arise from applying a generalized theoretical model to a real world scenario. For our application of the HSRF, we identified and considered the following cases:

FMU without a source: FMUs without sources are not routed. The harvest trigger variable (x_{it}) and additional constraints are omitted. As per the un-modified harvest scheduling model formulation, these FMUs can be scheduled for harvest and will contribute to the objective function, as well as the harvest flow and ending age constraints.

FMU with a single source: FMUs with a single source simply add their flow via the harvest trigger variable (x_{it}) into the "flow-in" side of the flow constraints for that particular source segment.

FMU with multiple sources: For multi-source FMUs, we create dummy flow variables for each possible source, and force their sum to be equal to the harvest trigger variable (x_{it}). Since the trigger variable is binary, this forces only one of the dummy flow variables to be active at a time. The dummy flow variables are then added into the flow-in side of the flow constraints for the various sources.

Source not in network: If a source of an FMU is not listed in the database of road segments, then that source is ignored. If none of the sources are listed, then the FMU is treated as having no source (see above).

Source that is also a sink: If an FMU uses a sink as its source, there is no need to route the FMU. Therefore, we do not route any FMU that has a sink as a source. This case is handled as if the FMU has no source (see above).

Sources that do not lead to a sink: Due to the flow constraints (2), if an FMU with a source cannot be routed to a sink, the FMU cannot be harvested. This is an unreasonable limitation that can lead to problem infeasibilities in conjunction with harvest-flow and ending-age constraints. To ensure that all sources can eventually reach a sink, we use a connectivity algorithm (described below) to subset the road database. Any source that does not lead to a sink will not be in the new "connected" database and will therefore be treated as a source not in the network.

Additional Line Graph Considerations: For our case study dataset, both sinks and sources were defined by road segments. For the standard network representation, we had to choose which of the two nodes that define the segment to consider as a sink/source for the system. For each sink/source segment, we randomly chose one of the two nodes to be the sink/source in the line graph. This maintains the same number of source and sink points between both formulations. Additionally, using both nodes as a source would force all FMU's to be considered FMUs with multiple sources, which would introduce additional constraints.

Connectivity Algorithm: To avoid requiring an FMU to be routed if there is no possible route to a sink, we subset the road database using a connectivity algorithm. This ensures that only road segments that can eventually reach a sink are considered for routing and re-construction. The algorithm creates a "connected list" of road segments that are used as the underlying network for route-finding, and disregards all disconnected segments.

Data Sets: The number of road segments and routed FMUs largely determines the number of additional constraints and binary variables in the problem formulation. To examine the computational performance and solvability of our model, we decomposed the OESF dataset into multiple datasets of varying size. We generated four additional scenarios, which varied between roughly 1,000 and 15,000 road segments, as well as using the full road network (Table 1).

3.5 Results

Table 1 shows solution times for the various OESF scenarios. By increasing the size of the road network, we increase the numbers of FMUs that are routed and find a general increase solution time, and in the solution's optimality gap. Optimality gaps are percentage gaps between the upper and lower bounds on objective function values that are established by the solver as it works to find better solutions. For example, an optimality gap of 5% means that the upper bound of the optimal solution is 5% greater than the value of the lower bound. After 12 hours, the smaller models were well under a 10% optimality gap, while the larger models continued to be difficult to solve.

Problem Set	Network	Time	Optimality Gap	Rows	Columns	Non-zeros	Binaries
1000	**LG**	493s	0.1	56,242	200,898	979,347	13,063
1000	TS	794s	0.1	38,289	159,910	874,009	4,399
5000	LG	12h	3.44	149,574	386,729	1,473,852	59,585
5000	**TS**	12h	1.62	73,751	207,761	1,014,686	23,432
10000	**LG**	12h	13.21	258,017	604,526	2,049,171	113,698
10000	TS	12h	43.17	115,459	266,083	1,179,372	46,002
15000	**LG**	12h	8.34	756,681	1,068,958	4,190,877	424,115
15000	TS	12h	66.36	151,661	315,978	1,320,657	65,373
Full	LG	24h	896	1,256,700	1,682,338	6,529,045	714,353
Full	**TS**	12h	194.06	258,691	440,972	1,787,852	121,385

Table 3-1: Achieved optimality gaps as the size of the road network is varied. Reported values for Rows, Columns, Nonzero and Binaries are post CPLEX's preprocessing and aggregation routines. Bolded Networks outperformed the alternate for that problem set.

The differences in solution quality between the LG and TS network representations are significant, but not conclusive. Both network representations were found to be desirable in certain instances. The LGR creates more binary variables and has a larger matrix, but the matrix is also sparser, with a lower percentage of nonzero values. For the smallest problem set, the LGR consistently outperformed the TSR in solution speed. Similarly, the LGR vastly outperformed the TSR for the 10,000 and 15,000 segment scenarios. However, for the full scenario, the LGR struggled to find an initial solution given 24 hours, and once found, CPLEX was able to make no progress in its branch and bound routine. However the TSR was able to achieve a significantly lower percentage gap in only 6 hours. Similarly, the TSR outperformed the LGR in the 5,000 unit scenario, but this difference was less drastic.

Both representations successfully implemented route-finding, and generated valid routes from harvested FMUs to the network sinks. As an example of the type of additional analysis that can be performed using route-finding, figure 5 highlights all roads used in the first three periods of harvest. This type of information is useful to planners and analysts to help decide what roads can be possibly considered for decommission or abatement.

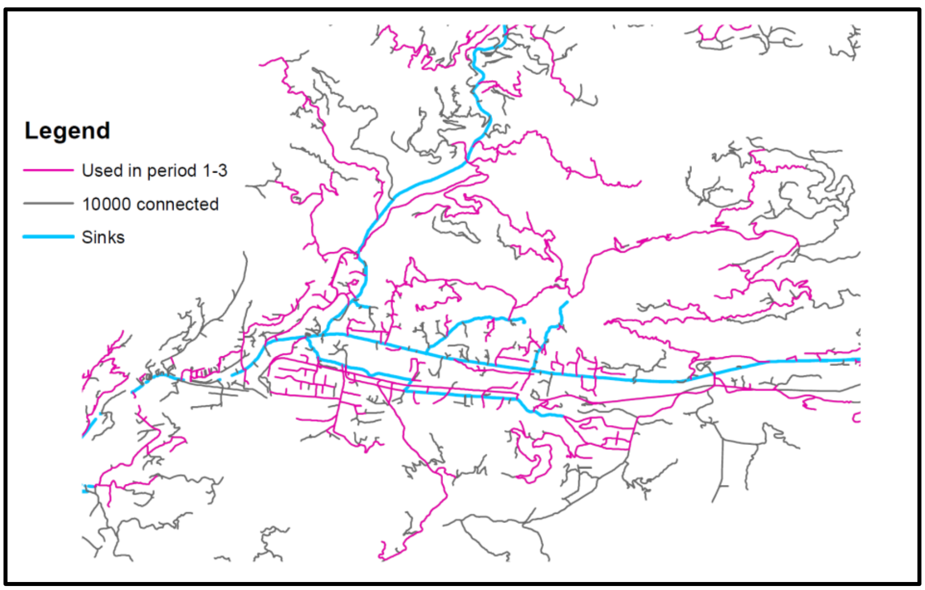

Figure 3-5: Example visualization of road segments used in the first 3 periods. Pink segments were used to route harvest in the first three periods, while grey segments were never used.

3.6 Discussion and Conclusion

In Forestry, the joint harvest-scheduling and road-access problem offers significant benefits over a decoupled, or hierarchical system. Incorporating road-access using route-finding allows the model the freedom to maximize the amount of overlap in hauling routes, and allows practitioners to investigate changes in the road network, at the cost of added complexity. Because these route-finding models depend on the specific size and configuration of the road network, it is important to understand how different network representations can affect the feasibility of incorporating route-finding into harvest-scheduling and road-access models.

In this study, we proposed a mixed integer optimization model called the Harvest-Scheduling with Route-Finding model (HSRF) to incorporate route-finding into a harvest-scheduling model. We applied our model to a case study in the Pacific Northwest using both the traditional network representation (TSR) of the road network as well as the line graph representation (LGR) that potentially alters the number of nodes and edges in the network. Our results show that the LGR consistently created larger, sparser matrices than the TSR that often allowed for easier solving. However, both network representations excelled depending on the specific problem set. In addition to potential improvements in solution times, the LGR may help facilitate the adoption of route-finding by requiring input data that more closely aligns with forest road databases. Overall, we find the LGR to be valid and useful tool to consider alongside the TSR in the forest analyst's toolbox.

The benefits of jointly optimizing harvest-scheduling and road-access decisions extend beyond improvements in net present value. Instead of requiring pre-defined routes, or determining them with post-processing, route-finding determines routes for the manager. This allows forest managers to rapidly test how alterations to the road network would affect both harvest and routing decisions. Additionally, these models can be extended to incorporate network specific constraints, such as requiring flow to reach multiple sinks (demand constraints), or limiting the amount of flow on specific segments (capacity constraints). Because these models are slow to solve for modest sized landscapes, improving solution time is an important step for the practical adoption of these joint harvest-scheduling and road-access models.

Although these concepts apply to many routing and supply-chain problems, the joint harvest-scheduling and road-access problem in forestry remains unreasonably difficult to solve for larger problems. Because of this, it is worth investigating the effects of our implicit assumptions about the system, including the representation of the network. In general, this work serves as a reminder to re-examine our modeling assumptions, and to consider how these seemingly subtle or obvious decisions can shape, and alter our analyses.

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3.7 References

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