Modelling Spatial Connectivity of Forest Harvest Areas: Exact and Heuristic Approaches

Pete Bettinger[a]
Warnell School of Forestry and Natural Resources, University of Georgia, 180 E. Green Street, Athens, Georgia, U.S.A.

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Abstract: A forest management planning process can involve the development of a tactical plan that illustrates for a land manager where to go and what to do within a specific period of time, acknowledging and satisfying all recognized management constraints. More often these days, forest management constraints address the size, timing, and placement of management activities. The optimization methods used to mathematically develop a forest plan, and to integrate spatial constraints into planning efforts are often referred to as exact and heuristic approaches. This paper describes how one might model spatial connectivity of forest harvest areas as constraints under both approaches, using two different representations of connectivity, the unit restriction model and the area restriction model. The heuristic approach to the latter has until now only been described using scientific notation. Here, we provide guidance for the programming logic.

1 INTRODUCTION

Forest management is an important aspect of modern society. Nations around the world act in various ways to address the use of these renewable resources, to balance the demand for wood and paper products with the demand for other ecosystem services such as the development and maintenance of recreational spaces and wildlife habitat, and the provisioning of water and sequestered carbon. Knowledge of the potential location of future forest management activities can help forest managers better account for spatial management restrictions and wildlife habitat concerns, and thus allow appropriate decisions to be made. In some cases the rules for the management of forests are embedded in laws and regulations (e.g., Maine Forest Service, 2017). In the absence of these, forest management may be influenced by the desires of certification programs (e.g., Forest Stewardship Council-US, 2019) or simply by the desires of the forest landowner.

Over the last three decades, the use of spatial dependencies for analysing appropriate actions has been increasingly suggested in the functional relationships that connect proposed management activities to economic, ecologic, or social outcomes. In the field of forestry, the use of a geographic concept, *adjacency*, has become an important method for assessing spatial dependencies, and the outcomes of these assessments subsequently are used to control (constrain) the assignment of management activities to forest areas.

There are many reasons why a specific forest landowner would want to develop a forest plan that addresses spatial issues such as adjacency of management activities, from concern over the cumulative effects of the management of their lands to compliance with laws and regulations (Bettinger and Sessions, 2003). Landowners often develop a forest plan to guide the implementation of management activities by forest managers. The closer a plan models the real world system in which the forest managers operate, the more likely the outcomes of forest management can trusted. However, forest planning problems with spatial connectivity constraints can be difficult to mathematically model. Often the number of spatial relationships that are needed to represent connectivity of management activities or the impact of management on wildlife habitat components increase exponentially as management unit size decreases and the scope of local analysis rules increase. Some examples include the examination of wildlife habitat conditions within

[a] https://orcid.org/0000-0002-5454-3970

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a certain distance of a proposed timber harvest, and the impact of that proposed harvest on minimum habitat suitability constraints (Bettinger and Boston, 2008), and the evaluation of the average size of a forest openings caused by proposed timber harvest activities, and the impact of that proposed harvest on constraints that limit maximum average opening sizes (SFI USA, 2022). The mathematical approaches that might be used to represent important spatial relationships within a forest planning or optimization context may overwhelm both the planner and the data development processes employed.

This paper describes the common ways in which adjacency of planned management activities is modeled in quantitative processes that lead to the development of a formal forest plan. The methods are aimed at the integration of these ideas as constraints with exact approaches to optimization of a forest plan through mixed integer programming, and with heuristic approaches to combinatorial optimization through processes such as simulated annealing, threshold accepting, or tabu search.

2 METHODS

The concepts described here refer to the development of a tactical forest plan (where to go, and what to do during specific periods of time). A mathematical recognition and acknowledgement that two proposed forest management activities are adjacent, in time and space, can be used as a constraint that limits one of them from being implemented through the tactical forest plan. The feasibility of forest plans, which guide the activities implemented by forest managers, should be sound, providing forest managers an opportunity to avoid mistakenly transforming the condition of a landscape to a state that may be not only undesirable, but also difficult to remedy in a short amount of time.

Management units (i.e., stands, polygons) are defined in modern times through the development of a geographic information system (GIS) database. These are contiguous areas of land that will be managed in the same way through time. They often include resources (e.g., trees) that have similarities or are managed similarly. One example would be an area of planted pine trees, where all of the trees are the same species and age, and thus managed as an even-aged system. Another example may be an area containing a collection of heterogeneous tree species and tree ages that are managed together as an uneven-aged system. *Adjacency* refers to the proximity of each management unit. In forest management, the most common type of adjacency relationship between two management units is that they share a side (or in GIS, a line). However, an adjacency relationship may suggest that two management units (a) only share a point (vertex) in geographical space, of (b) share not even a single vertex but have polygon vertices that are within some assumed distance (e.g., less than 100 m apart in geographical space).

Described below are methods for addressing constraints of an optimization process. Constraints control the amount, timing, and placement of management activities when one seeks to minimize or maximize some objective function (e.g., maximize revenue). Two types of adjacency relationships are commonly recognized in forest management planning to control the timing and placement of final forest harvests (clearcuts): the unit restriction model and the area restriction model (Murray 1999).

2.1 Unit Restriction Adjacency

The concept of *unit restriction adjacency* in forest and natural resource management is often used within mathematical processes related to the development of a tactical forest plan (where to go, and what to do during specific periods of time). Unit restriction adjacency constraints would prevent the assignment of similar activities to two adjacent management units during a specific period of time. For example, if the final felling of trees in two management units were under consideration, a unit restriction adjacency constraint would prevent the assignment of the fellings to occur during the same period of time. The period of time is also referred to the *green-up period*, which denotes the amount of time that the regenerated forest in one management unit (the one whose trees have been previously harvested) to grow to a desired height (hence *green up*). In the northwestern United States, the green-up period is often assumed to be 5 years on private lands, yet it can be much longer on public lands. The length of the green-up period is often defined by law or by policy.

2.1.1 Exact Approach

When employing unit restriction adjacency of forest management activities and using an exact approach suitable for mixed integer programming optimization techniques (branch and bound, cutting plane, etc.), one would develop *pairwise constraints* that limit the ability of the process from selecting for management two adjacent neighbours during the same time period or green-up period. For example, to prevent the trees in both management unit 1 and management unit 2, which are physically adjacent, from being harvested during the same period of time (e.g., time period 1) a constraint would be developed:

$$MU1P1 + MU2P1 <= 1 \quad (1)$$

Here, the decision variable MU1P1 represents the potential harvest of trees in management unit 1 during time period 1. This approach assumes that the decision variables are assigned only integer values, where 1 = yes, harvest the trees in the management unit, and 0 = no, do not harvest the trees in the management unit. Obviously, only one of the two choices would be possible with this constraint. For multiple time periods (a green-up period that is longer than a single time period), multiple pairwise constraints may be necessary.

$$MU1P1 + MU2P1 <= 1 \quad (2)$$

$$MU1P1 + MU2P2 <= 1 \quad (3)$$

$$MU1P1 + MU2P3 <= 1 \quad (4)$$

In the example above, if the trees in management unit 1 are scheduled for harvest during time period 1 (e.g., MU1P1 = 1), then the trees in management unit 2 are not allowed to be harvested during time periods 1, 2, and 3.

What may not be obvious in this approach is that the equations reflecting the constraints must be constructed prior to solving the problem with an optimization technique. If the green-up period changes (lengthens or shortens), or the rules for defining adjacent land areas change, the equations would need to be re-developed.

2.1.2 Heuristic Approach

When a forest planning problem is being solved (attempted to be optimized) with a heuristic approach, computer logic (If-Then-Else statements, For-Next loops, etc.) is used to assess constraints in real time. For example, if a heuristic is attempting to schedule a final harvest for management unit 1, it assesses all of the potential constraint violations prior to formally assigning the harvest period to that management unit. To enable the assessment of adjacency constraints within a heuristic, a list of the adjacency relationships among the management units is often held in memory of the computer program, and this list is accessed when it is needed. The list may be as simple as:

```
1,2
1,3
1,4
2,1
2,12
3,1
3,4
...
```

This adjacency list suggests that management unit 1 is adjacent (however defined) to management units 2, 3, and 4. The list is redundant, as it also indicates that in addition to management unit 1 being adjacent to management unit 2, management unit 2 is adjacent to management unit 1. To improve the efficiency of this process, the list of adjacency relationships might be sorted by management unit number, and pointers might be developed to quickly access the beginning and ending set related to a specific management unit. For example, the pointers for management unit 2 are 4 (beginning line number) and 5 (ending line number). This structure might be composed of a single column vector once the beginning and ending points for each management unit are known.

As an example of how a heuristic process would assess the unit restriction adjacency constraint, imagine that the trees in management unit 2 are potentially being scheduled for final harvest during time period 1. The logic within a heuristic would check all of the neighbours of management unit 2 to determine whether their trees are currently scheduled for harvest during the same period of time.

```
Constraint violation = 0
For a = Beginning pointer (Management Unit 2) to Ending pointer (Management unit 2)
   If (Potential harvest period (Management unit 2) = Scheduled harvest period (Adjacency list (a))) Then
      Constraint violation = 1
   End If
Next a
```

Here, *potential harvest period (Management unit 2)* is time period 1, and the scheduled harvest periods of neighbours are determined by understanding who the neighbours are from the adjacency list. In this approach, there would be no need to re-develop equations to assess the adjacency relationships. One would only need the assumption of the green-up period length to enable the logic to work during the heuristic search process. If the green-up period were longer than one time period within the time horizon, the logic would expand to:

```
LowerPeriod = Potential harvest period
(Management unit 2) - (Greenup window -
1)
UpperPeriod = Potential harvest period
(Management unit 2) + (Greenup window -
1)
```

```
Constraint violation = 0
For a = Beginning pointer (Management
Unit 2) to Ending pointer (Management
unit 2)
   If (Scheduled harvest period
   (Adjacency list (a)) >= LowerPeriod
   AND Scheduled harvest period
   (Adjacency list (a)) <= UpperPeriod)
   Then
      Constraint violation = 1
   End If
Next a
```

Here, *LowerPeriod* and *UpperPeriod* represent the bounds on the green-up period, or the time periods that represent the beginning and ending of the green-up period with respect to the potential schedule of a harvest in Management unit 2 during time period 1. Of course, some minor additional logic would be necessary to ensure that *LowerPeriod* and *UpperPeriod* are reasonable (i.e., greater than 0 and less than or equal to the total number of time periods). One advantage to the heuristic approach is that the entire set of equations that define the adjacency relationships need not be pre-defined, as the relationships are assessed in real time, when needed.

2.2 Area Restriction Adjacency

The concept of *area restriction adjacency* in forest and natural resource management is also used within mathematical processes related to the development of a tactical forest plan. In fact, this model of controlling adjacent management activities is more closely associated with common practice than the unit restriction model, as management units defined in a geographic information system may be of various sizes, and combining them for on-site management may be more practical than managing them separately.

Area restriction adjacency constraints would *allow* the assignment of similar activities to two or more adjacent management units during a specific period of time, as long as the total size of the contiguous set of activities does not exceed some maximum, assumed size. For example, if the final felling of trees in two management units were under consideration, an area restriction adjacency constraint would allow the assignment of the fellings to occur during the same period of time only if their total size did not exceed some assumed maximum size. Depending on the size of management units (polygons) developed within a geographic information system, and the assumed maximum size, this collection of adjacent management units with similar activities assigned can be brief (2 or 3 management units) or extensive (many management units). For final harvests, the complicating factor is the green-up period, and therefore here, the constraint needs to be assessed from the perspective of each management unit within the collection of adjacent management units.

2.2.1 Exact Approach

Several methods for developing the equations that would allow multiple forest management units that are connected to be managed during a common period of time have been described in the literature (e.g., Meneghin et al. 1998, Murray and Church 1996). For this illustration we use the path model that was described by McDill et al. (2002), as it concisely illustrates an exact approach for modelling area restriction adjacency.

Imagine that there are a collection of forest management units of various sizes, and that there is some assumed maximum area size (*A*) for final harvests of the trees. Beginning with any two adjacent pairs of management units, if the combined area of these exceeds *A*, then a pairwise adjacency constraint can be developed to prevent both of the management units from being scheduled for harvest during a specific period of time (i.e., the length of the green-up period), just as we noted earlier. However, if the combined size of the two management units is less than *A*, it is possible that both can be scheduled for harvest during the same period of time. In this latter case, an examination of all of the adjacent neighbours to these two management units would be made to define the clusters of management units whereby the last one added would force the total size of the cluster to exceed *A*.

For example, assume management units 1-4 are adjacent in one form or another. Assume the areas of these management units are respectively 10 ha, 12 ha, 15 ha, and 10 ha. If *A* = 40 ha, then all four management units should not be scheduled for a final harvest during a period of time defined by the green-up period. The exact approach constraints developed to prevent scheduling all four during time period 1 of a planning process would be devised in this manner

$$MU1P1 + MU2P1 + MU3P1 + MU4P1 \le 3 \qquad (5)$$

which allows up to three of the management units to be scheduled for a harvest during time period 1, but not all four of them. In other words, from none to any three of the management units can be scheduled for harvest during time period 1 based on their adjacency relationships.

The "path" in the path model reflects the connectivity of management units. Some management units in the resulting cluster may not be themselves adjacent, yet a cluster is formed that connects all of those considered. All possible paths that originate from each management unit, that relate to the possible final harvest of the trees in that management unit during different periods of time, must be assessed to develop these constraints. Further, redundant and dominated constraints (made ineffective based on other constraints) should preferably be avoided, which may add considerable time to the development of the set of exact approach constraints.

As with the unit restriction model, equations reflecting the constraints must be constructed prior to solving the problem. If the green-up period changes (lengthens or shortens) the equations would need to be re-developed. The larger the *A* (maximum size) and the longer the green-up period, the larger becomes the set of constraints needed. This development and management of constraint equations to represent the adjacency relationships is perhaps the most important disadvantage of using an exact approach to model spatial connectivity.

2.2.2 Heuristic Approach

As an example of how a heuristic process would assess the area restriction adjacency constraint, imagine that the trees in management unit 2 are potentially being scheduled for final harvest during time period 1. The logic within a heuristic would check all of the neighbours and place them in a set of management units that forms a *harvest block*, as long as the trees within the neighbouring management units are already scheduled for harvest within the green-up period, and as long as the total size of the harvest block is less than the maximum size (*A*) allowed. The example below begins with management unit 2, and illustrates the building of harvest block based on the prior harvest schedules assigned to nearby neighbouring management units.

```
Constraint violation = 0
Block size = Size (Management Unit 2)
Queued (1) = Management Unit 2
Do While Queued (1) > 0
   For a = Beginning pointer (Queued (1))
   to Ending pointer (Queued (1))
      If (Potential harvest period
      (Queued (1)) = Scheduled harvest
      period (Adjacency list (a))) Then
         Place Adjacency list (a), the
         adjacent neighbour, in the next
         empty cell of the Queued array.
         Block size = Block size + Size
         (Adjacency list (a))
         If (Block size > A) Then
            Constraint violation = 1
            Exit Loop
         End If
      End If
   Next a
   "Seated" Management unit = Queued (1),
   remembering member(s) of the harvest
   block
   The Queued array is then adjusted,
   moving neighbouring management units
   up 1 place
Loop
```

In addition to this abbreviated process, several additional checks and balances may be needed. For example, when neighbouring management units are identified, they are ignored if they are already present in the Queued array or if they are "Seated" as part of the harvest block. If the logic suggests a constraint violation has occurred, the resulting harvest block is too large, and the proposed management activity originally under consideration (in this case, the harvest of trees in management unit 2 during time period 1) is disallowed. However, if the resulting harvest block does not exceed the maximum allowed size, the proposed management activity may be allowed to be scheduled within the framework of a *s*-metaheuristic (e.g., simulated annealing, tabu search), assuming the solution is feasible with respect to all other constraints and other heuristic rules allow the change to be made to the current feasible solution.

The main disadvantage of this heuristic approach to modelling spatial connectivity is the programming logic needed to efficiently and correctly represent the development of a sprawling harvest block. Further, when the green-up period is longer than one time period, the assignment of harvest period to the focal management unit in the process (the management unit in position Queued(1)) defines the *LowerPeriod* and *UpperPeriod* that were mentioned earlier. These periods of time only relate to management unit 1, and subsequently they need to be adjusted to assess constraint violations related to all of the management units in the Queued array (making them temporarily the focal unit in this process).

2.3 Case Study

The application of unit restriction and area restriction adjacency constraints is applied to a forested tract of land situated in the western United States. The management plan devised for this property has a 30-year time horizon that consists of six, 5-year time periods. The goal of the planning process is to provide a guide to the forest managers, suggesting which management units to harvest trees in each of the six time periods, while minimizing deviations from a pre-defined sustainable flow of wood products (13,950 thousand board feet[1] of wood per 5-year time period). When the area restriction adjacency constraint is employed, the maximum size was assumed to be 48.6 hectares (120 acres).

The exact approach described for the URM case was formulated as a mixed integer programming model and solved using Lingo Extended 19.0 (Lindo Systems Inc., 2022). The heuristic approaches that are described here for both the URM and ARM cases embedded into a threshold accepting heuristic model that employed search reversion and 2-opt moves (Bettinger et al., 2015). The exact model produced the optimal solution to the problem, while the heuristic model produced the near-optimal solutions to the associated problems.

2.3.1 Landscape Data

The case study forest (1,841.5 hectares) is contiguous (Figure 1) and composed of 87 management units that contain Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) trees of various ages. This case study forest has been employed in several other research studies regarding optimization methods for developing forest plans (Akbulut et al., 2017, Bettinger et al., 2015, Restrepo et al., 2022).

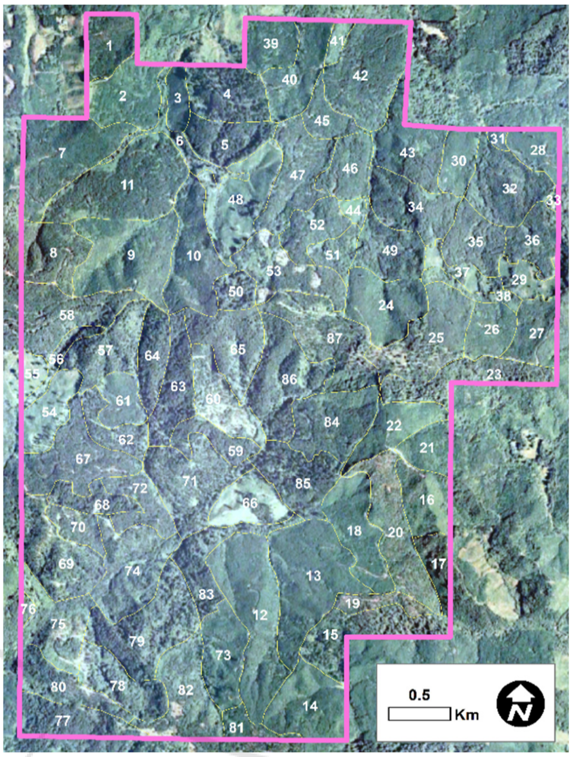

Figure 1: The contiguous case study forest area.

3 RESULTS

For the case study landscape described above, the exact method for developing a forest plan that accommodates unit restriction adjacency constraints for final harvests requires 1,260 non-redundant pairwise adjacency constraints when the green-up period is one time period. As the size of the green-up periods increases, the number of pairwise constraints for this case study forest increases: 3,360 pairwise constraints for two-period green-up, 5,040 pairwise constraints for three-period green-up, 6,300 pairwise constraints for four-period green-up, and so on. The increase is not linear, as the green-up period extends beyond the last period of time horizon (for *UpperPeriod*), or before the first period of the time horizon (for *LowerPeriod*), fewer pairwise constraints are necessary. The heuristic method requires no pre-defined adjacency constraints, as it checks the constraint violations with each attempted adjustment to feasible solutions in real time as the optimization problem is being solved. The logic required to assess the constraints within a heuristic can be as simple as the six lines of code noted above, however, additional logic would be required to read and store the adjacency list, and to create the pointers for each stand to efficiently access the adjacency list. An example forest plan, or coloured graph, that represents the planned harvest period for each management unit, recognizing unit restriction constraints, is illustrated in Figure 2.

The exact method for developing a forest plan that accommodates area restriction adjacency constraints for final harvests requires 2,046 non-redundant, non-dominated adjacency constraints when the green-up period is one time period. As the number of green-up periods increases, the number of constraints for this case study forest increases substantially: 22,040 constraints for two-period green-up, 74,988 constraints for three-period green-up, and 146,238 constraints for four-period green-up. Like the

[1] a board foot is 1 inch thick × 1 foot tall × 1 foot wide, or 2.54 cm thick × 30.48 cm tall × 30.48 cm wide.

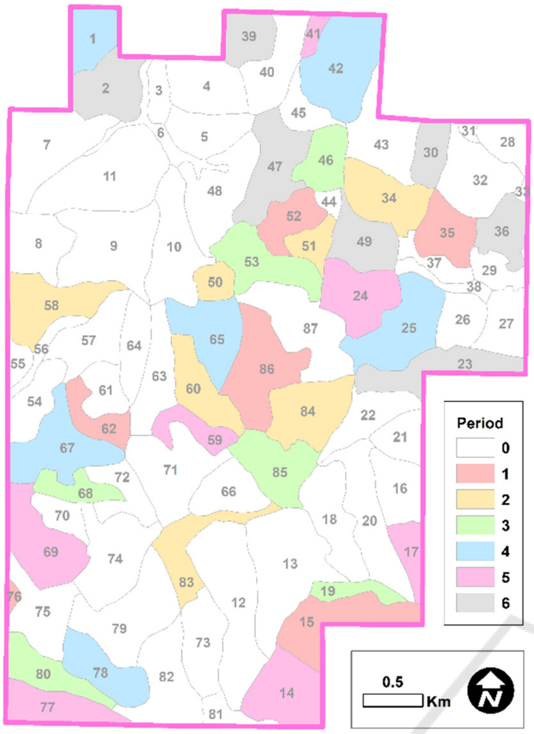

Figure 2: A forest plan that indicates the time period to harvest the trees in each management unit, while accommodating unit restriction adjacency constraints with a green-up length of one time period.

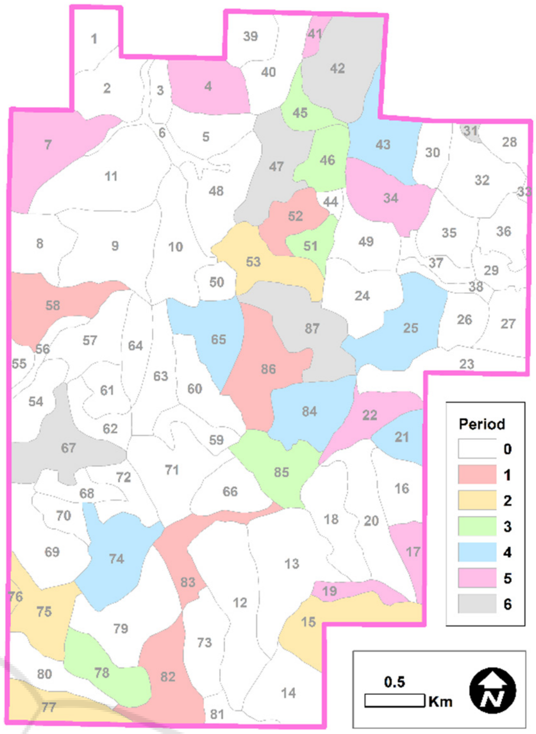

Figure 3: A forest plan that indicates the time period to harvest the trees in each management unit, while accommodating area restriction adjacency constraints with a green-up length of one time period.

previous case, the increase is not linear, but is it certainly more substantial.

The combinations of management units that just exceed the maximum area size, as the last one is added, can be large when the management units are small relative to the maximum area size. For this case study landscape, one non-dominated area restriction constraint contained six management unit decision variables when the maximum area size was 48.6 ha, and 8 non-dominated area restriction constraints contained five management unit decision variables. An example forest plan, or coloured graph, that represents the planned harvest period for each management unit, recognizing area restriction constraints, is illustrated in Figure 3.

As suggested earlier, when it is necessary, removing the redundant and the dominated constraints can be cumbersome. For example, the constraint

$$MU1P1 + MU2P1 + MU3P1 + MU4P1 <= 3 \quad (6)$$

is dominated by

$$MU1P1 + MU2P1 + MU4P1 <= 2 \quad (7)$$

since if the latter is true, then the former must also be true.

As noted earlier, one of the challenges when utilizing an exact method for constraining the timing and placement of forest management activities is in reconstructing the area restriction model adjacency constraints when the maximum area size or the green-up period length changes. For example, a landowner may wish to assess through modelling the impact of various green-up or maximum final harvest size policies on the production potential or economic outcomes of a forest plan. For these purposes, the development of adjacency constraints for an exact method would likely require a separate computer program to assess the relationships and remove the redundant and dominated constraints.

As in the unit restriction case, the heuristic method requires no pre-defined area restriction adjacency constraints, as it checks in real time (during the optimization process) the constraint violations with each attempted adjustment to feasible solutions. However, the logic required to assess the constraints within a heuristic can require an extensive amount of computer code to track the so-called *queued* and *seated* management units noted earlier.

4 CONCLUSIONS

Described in this paper are methods for modelling the connectivity of forest harvest areas, with particular emphasis on the development of a tactical forest management plan that prevents adjacent final harvests of trees in management units located across a forested area. Two common operations research approaches for developing tactical forest management plans that involve exact and heuristic methods were described. The exact methods for modelling unit restriction adjacency and area restriction adjacency are well known within the forestry community (e.g., McDill et al. 2002). The heuristic method for assessing unit restriction adjacency has been described in a number of published papers over the last two decades (e.g., Akbulut et al., 2017, Bettinger et al. 2015, Bettinger and Boston 2008). The logic for assessing area restriction adjacency has only been described in a theoretical sense in prior works, therefore the process described here may be one of the first explicit examples of how one might model area restriction adjacency using computing logic.

As was illustrated in this paper, the number of *a priori* defined constraints for exact URM and ARM approaches that acknowledge and control the adjacency of management activities can be quite extensive, depending on the spatial management unit size and the scope of local analysis rules. In contrast, the heuristic approaches require only logic to assess these relationships when they are needed during the mathematical scheduling of management activities. Regardless of the approach for developing a forest plan or assessing the impact management activities across a landscape, the exact and heuristic approaches have both advantages and disadvantages that may be of importance to scholars and practitioners. Future work might involve studies designed to further understand the time and effort needed to accommodate these approaches as property size increases and as spatial unit sizes change. These investigations would advance our understanding how the results from applying these methods may be generalizable across different forest landscapes.

REFERENCES

Akbulut, R., Bettinger, P., Ucar, Z., Obata, S., Boston, K., Siry, J. (2017). Spatial forest plan development using heuristic processes seeded with a relaxed linear programming solution. Forest Science. 63(5): 518-528.

Bettinger, P., Boston, K. (2008). Habitat and commodity production trade-offs in Coastal Oregon. Socio-Economic Planning Sciences. 42(2): 112-128.

Bettinger, P., Demirci, M., Boston, K. (2015). Search reversion within s-metaheuristics: Impacts illustrated with a forest planning problem. *Silva Fennica. 49(2)*: article id 1232.

Bettinger, P., Sessions, J. (2003). Spatial forest planning: To adopt or not to adopt? Journal of Forestry. 101(2): 24-29.

Forest Stewardship Council-US (2019). FSC-US Forest Management Standard (V1.1), Complete with: Family forest indicators and guidance and supplementary requirements for lands managed by the USDA Forest Service. Forest Stewardship Council US, Conifer, CO.

Lindo Systems Inc. (2022). LINGO Extended 19.0. Lindo Systems Inc., Chicago, IL.

Maine Forest Service (2017). The forestry rules of Maine 2017, A practical guide for foresters, loggers and woodlot owners, 2nd edition. Maine Department of Agriculture, *Conservation & Forestry, Maine Forest Service, Augusta*, ME.

McDill, M.E., Rebain, S.A., Braze, J. (2002). Harvest scheduling with area-based adjacency constraints. Forest Science. 48(4): 631-642.

Meneghin, B.J., Kirby, M.W., Jones, G.J. (1988). An algorithm for writing adjacency constraints efficiently in linear programming models. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO. General Technical Report RM-161. pp. 46-53.

Murray, A.T. (1999). Spatial restrictions in harvest scheduling. Forest Science. 45(1): 45-52.

Murray, A.T., Church, R.L. (1996). Analyzing cliques for imposing adjacency restrictions in forest models. Forest Science. 42(2): 166-175.

Restrepo, H.I., Bettinger, P., Bullock, B.P. (2022). A theoretical minimum solution for heuristics: The case of the spatial timber harvest problem. *Computers & Operations Research*. 143: Article 105792.

SFI USA. (2022). SFI 2022 forest management standard, Section 2. *SFI USA, Washington*, D.C.