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A hierarchical planning system to assess the impact of operational level flexibility on long-term wood supply

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Abstract

Operational level flexibility in the choice of silvicultural treatments allows to mitigate the impact of uncertain demand on supply chain performance. Silvicultural treatments dictate the species and quantity harvested from forest stands. However, its impact on wood supply sustainability is not clearly understood. This study proposes a simulation-optimization system to model hierarchical forest management planning with an objective to examine the impact. The system consists of mathematical models to develop hierarchical plans, i.e. strategic, tactical and operational. In the system, the strategic model is first solved to determine the annual allowable cut (AAC). Next, the tactical model allocates cutblocks to annual plans, also prescribing silvicultural treatments. The subsequent operational level model generates monthly plans in a rolling planning basis to satisfy prevailing demand. Upon execution of all operational level plans, the forest inventory is updated and the change in AAC is evaluated. The system was implemented to a case study in Quebec, Canada. Permitting silvicultural flexibility at the operational level led to profit improvements between 2-3.7% over a 100-year horizon. Significant impact on long-term wood supply was not observed in this case. The proposed system can help forest planners and supply chain managers better integrate their respective needs.

Keywords: Hierarchical forest management planning model, wood supply, simulation-optimization, wood procurement agility, silviculture.

1. INTRODUCTION

The potential to generate value from forest resources is dependent on forest management plans. Developing an optimal plan is a complex challenge due to the uncertain and dynamic nature of the forest systems, social constructs and economic parameters. The planning problem is exacerbated by imprecise knowledge of inventory (Thompson et al. 2007). In this context, it is important to first develop a credible plan and permit flexibility to readjust plans as new information becomes available. Permitting flexibility generates value adding opportunity also for wood procurement systems (WPS) through an improved agility to satisfy supply chain's timber demand, which is characterised by uncertainty. In the context of this study, uncertainty relates to the unexpected periodic fluctuation in the raw material orders placed by forest products companies. Agility is the ability to respond promptly and effectively to the unexpected fluctuations in demand (Gautam et al. 2013). One possible way to improve WPS agility is through flexibility in the choice of silvicultural treatments at the operational level instead of fixing the decision at an upper hierarchy. A series of silvicultural treatments are prescribed to a stand throughout a rotation to achieve management goals. The treatments include harvesting, regeneration and stand-tending; the focus of this study is on harvesting. As such, silvicultural treatments dictate the array of assortments and their quantities produced from cutblocks (Lussier 2009). Practitioners could be provided with a list of ecologically feasible silvicultural treatments for a cutblock. A selection could then be made once market demand materializes. Such practice allows better alignment of supply with demand; Gautam et al. (2015) report a profit increase of up to 5.5%.

From a hierarchical forest management planning perspective, silvicultural flexibility implies postponement of the final decision-making rights to the operational level. This leads to a situation of distributed decision making as described by Schneeweiss (2003). Hierarchical approach is used in forest management planning due to the complexity associated with capturing all elements of forest systems in a single model (Church 2007). First, a strategic plan is devised taking into consideration long-term forest productivity, and ecological and social concerns (Gunn 2009). The outcome of the plan is the determination of annual allowable cut (AAC) by species group and silvicultural treatments to be applied. Subsequently, a tactical plan spatially disaggregates the volume targets while considering economical, ecological and social constraints. The process results in the identification of cutblocks. Silvicultural treatments are prescribed ensuring that the total volume harvested in the forest will be within the target range set at the strategic level. Further down the hierarchy, operational plans outline detailed schedules to meet industrial demand for timber.

From a supply sustainability perspective, altering silvicultural treatments at the operational level could impact the AAC, despite the ecological suitability of the applied treatment. The extent of the impact will, however, vary based on the total harvest at the forest level. A number of studies have demonstrated the linkage between harvest levels and AAC (Armstrong 2004; Paradis et al. 2013). Altering silvicultural treatment in a cutblock also changes the total volume harvested. However, we hypothesize that if the total volume harvested in a forest is well below the AAC, the incremental impact induced by altering silvicultural treatment will be negligible. Conversely, if the harvest level is close to the AAC, there will be a greater chance of a significant impact on the

AAC. A mechanism capable of simulating the hierarchical framework of forest management is needed to carry out the analysis.

A number of studies have proposed procedures to simulate the hierarchical framework of forest management. Weintraub and Cholaký (1991) presented a manual approach to improve consistency between strategic and tactical planning levels. At the strategic level, the forest was divided into smaller zones and aggregated information was used. The outcome of the strategic model provided directives for the tactical model in terms of timber production goals as well as road building budget. The tactical level model subsequently maximized profit using disaggregated information under constraints imposed by the strategic level plan. If there were inconsistencies between the two levels, adjustments were made at both levels, followed by a second iteration of the process. In Nelson et al. (1991), a long-term, strata based, model was first used to determine volume targets for 15 decades. Subsequently, Monte Carlo integer programming technique was used to solve spatial harvest scheduling problem with adjacency constraints for the first three decades. In the bottom-up phase, the long-term plan was solved again with the solution of the short-term plan imposed into the first three decades. Davis and Martell (1993) presented a system that allows tactical level decision to be made based on knowledge of its long-term implications. Cea and Jofré (2000) proposed a method to simultaneously consider strategic and tactical planning. First, aggregation of forest stands was done through a cluster analysis technique to form macro stands. A strategic plan for a 45-year horizon was then developed to set volume targets and decide on plant locations. The plan is disaggregated at the tactical phase where decisions were made on roads to be built, cutblocks to be harvested, and

volumes to be transported from cutblocks to mills. Next, the extent of discrepancy in harvest and road costs between the two levels were measured. If deemed unacceptable, further iterations are run re-aggregating the first period solution to a lesser extent until an acceptable strategic-tactical solution was attained. Beaudoin et al. (2008) used an anticipative approach to ensure feasibility of the tactical plan at the operational level. At the tactical level, a number of candidate plans were generated with decisions on harvesting, transportation and inventory. The operational level logistical costs associated with the developed plans were then anticipated for each of the candidate plans. The final decision-making at the tactical level (selection of a plan from amongst the candidate plans) was influenced by the anticipated information, eliminating plans that would be infeasible at the operational level. A similar concept was applied by Marinescu and Maness (2010) who proposed an algorithm that links models to support decision making at different hierarchies, between a multi-criteria timber allocation model and a sawmill optimization model. This algorithm allowed iterative negotiation between the models to maximize value at both levels.

To our knowledge, a system to anticipate the strategic level impact of operational level activities has not yet been proposed in the literature. This study proposes a simulation-optimisation system to model the development of three-level hierarchical forest management plans, strategic-tactical-operational, in a sequential manner. The system is subsequently implemented iteratively to a typical forest management unit in Eastern Canada to anticipate the impact of operational level silvicultural flexibility on long-term wood supply.

2. AN OVERVIEW OF THE PROPOSED PLANNING SYSTEM

The proposed system simulates iterative development and execution of hierarchical forest management plans on a rolling planning horizon basis. This process of development and implementation of plans at each hierarchy is shown in Figure 1. First, an optimization model develops a long-term strategic plan. The model, with an objective to maximize AAC, sets volume targets for the subsequent tactical planning. At the tactical level, an optimization model is used to develop five annual plans. These annual plans contain a list of cutblocks allocated to each year, and a silvicultural treatment prescription for each cutblock. As such, the strategic and tactical plans are developed from the land owner's perspective, with the goal of sustaining long-term wood supply. The unique aspect of the proposed approach is that non-prescribed but potential alternative silvicultural treatments for all cutblocks are made available at the operational level. The operational level plans are developed from the perspective of a wood supplier attempting to maximize economic value. At the operational level, another optimization model is used to develop monthly schedules to meet the prevailing demand. A simulation procedure is employed to generate random demand for the upcoming year which the WPS attempts to fulfill by developing operational level plans. The operational plans (annual) are executed sequentially, but within each year monthly plans are developed in a rolling planning horizon basis.

Once all the tactical level plans (5 annual plans) are executed at the operational level, the land base inventory is updated to account for the volumes that were harvested. Next, the AAC is recalculated followed by subsequent iterations of the entire process. At each iteration of this simulation-optimization process, fluctuation in AAC and

profits are recorded. Profit values are obtained at the operational level; it represents the revenue generated through fulfilling customer demand minus the costs. The next subsection provides a description of the models used in each of the planning hierarchy.

2.1. Hierarchical planning models

The strategic level planning model is formulated as a model II linear program (Johnson and Scheurman 1977) in SilviLab, a modelling platform developed by FORAC research consortium for forest growth simulation and optimization (Simard et al. 2012). The model is expanded to incorporate different stand types and silvicultural treatments. The model is presented below:

Sets

W: set of stand types
S: set of Silvicultural treatments
T: set of time periods

Parameters

V_{wsij} Volume yield in stand type w regenerated in period i and harvested in period j applying silvicultural treatment s .
 θ Number of periods before zero in which the oldest age class present in period one was regenerated.
 Z Minimum harvest age.
 α Maximum percentage deviation (in decimal) in harvest volume between subsequent periods.

Decision variables

x_{wsij} Area of stand type w that was regenerated in period i to harvested in period j using silvicultural treatment s
 x_{wsi}^L Area of stand type w regenerated using silvicultural treatment s in period i and left unharvested in the planning horizon

Objective function

$$(1) \quad \text{Maximize volume harvest} = \sum_w^W \sum_s^S \sum_j^T \sum_{i=-\theta}^{j-Z} V_{wsij} x_{wsij}$$

179

Subject to,

$$(2) \quad \sum_w^W \sum_s^S \sum_j^T x_{wsij} + x_{wsi}^L = A_i \quad i = -\theta, \dots, 0$$

$$(3) \quad \sum_w^W \sum_s^S \sum_{k=j+Z}^T x_{wsjk} + x_{wsi}^L = \sum_w^W \sum_s^S \sum_{i=-\theta}^{j-Z} x_{wsij} \quad j = 1, \dots, T$$

$$(4) \quad \sum_w^W \sum_s^S \sum_{i=-\theta}^{j-Z} V_{wsij} x_{wsij} \leq \sum_w^W \sum_s^S \sum_{i=-\theta}^{j-Z} (1 + \alpha) V_{wsij} x_{wsij} \quad j = 1, \dots, T - 1$$

$$(5) \quad \sum_w^W \sum_s^S \sum_{i=-\theta}^{j-Z} V_{wsij} x_{wsij} \geq \sum_w^W \sum_s^S \sum_{i=-\theta}^{j-Z} (1 - \alpha) V_{wsij} x_{wsij} \quad j = 1, \dots, T - 1$$

$$(6) \quad x_{wsij}, x_{wsi}^L \geq 0$$

180

181 The objective function (Equation 1) of the model is to maximize volume
 182 harvested over the planning horizon. x_{wsij} is the decision variable corresponding to area
 183 (ha) of stand type w born in period i , harvested in period j using silvicultural treatment s .
 184 V_{wsij} represents the yield ($\text{m}^3 \cdot \text{ha}^{-1}$) in stand type w , in period j , regenerated in period i
 185 and applied silvicultural treatment s . Equation 2 and 3 are area accounting equations;
 186 the equations track the transition of the stands over the course of the planning horizon
 187 as different treatments are prescribed. The maximum allowable fluctuation in volume
 188 harvested from period to period is regulated by equations 4 and 5. Finally, non-
 189 negativity restrictions are assigned to the respective variables using equation 6.

The tactical model is a spatial model that minimizes volume allocation to each of the time periods while meeting volume targets set at the strategic level. In this way, all annual allowable cut can be allocated for harvest. It is assumed that the cutblocks eligible for harvest have been delineated and the data is available for the tactical model.

Sets

T : set of time periods

H : set of cutblocks

S : set of silvicultural treatments

A : set of species

Parameters

V_{hsa} Volume of species a available in cutblock h when subjected to silvicultural treatment s (m^3).

N_h Set of adjacent cutblocks.

L_{sat} Volume target of species a in period t under silvicultural treatment s .

Decision Variables

O_{hst} 1, if cutblock h is allocated for harvest under silvicultural treatment s in period t ,
0, otherwise

Objective Function

$$[7] \quad \text{Minimize volume allocation} = \sum_h \sum_a \sum_s \sum_t V_{hsa} O_{hst}$$

Subject to,

$$[8] \quad \sum_h V_{hsa} O_{hst} \geq L_{sat} \quad \forall s, a, t$$

$$[9] \quad \sum_s \sum_t O_{hst} \leq 1 \quad \forall h$$

$$[10] \quad \sum_{h \in N_h} \sum_s O_{hst} \leq 1 \quad \forall t, N_h$$

The objective of the model is to minimize the total volume harvested (equation 7) of species a from cutblock h using silvicultural treatment s in period t . Equation 8 forces the model to meet volumes targets set by the strategic model. Equation 9 ensures that

only one silvicultural treatment is applied to each of the selected cutblock. Finally, equation 10 prohibits the harvesting of adjacent cutblocks.

As this is a spatial harvest scheduling problem, the solution time grows rapidly with increasing problem size, making it a NP-hard problem (Boston and Bettinger 1999). Thus, a heuristic technique, Monte Carlo integer programming, is used to obtain a solution in a practical time frame. Monte Carlo integer programming is an algorithm that generates a feasible plan through random selection of cutblocks. The flowchart in Figure 2 illustrates the technique. For each year, the algorithm generates a number of plans with different combination of cutblocks. Allocations are made to a specific plan until volume targets set at the strategic level are met. In selecting a cutblock for allocation under a specific treatment, the algorithm verifies that the adjacency constraints are respected. The algorithm terminates (i) if volume targets are met, or (ii) after a specified number of attempts to find a non adjacent cutblock. Once all plans are developed, the algorithm selects the one closest to the target for implementation. The algorithm was executed in Microsoft Excel 2010 using Visual Basic for Applications (VBA).

The output of the tactical plan is a list of cutblocks available for harvest with a silvicultural treatment prescribed to each cutblock. Non-prescribed but potential alternative silvicultural treatments for all cutblocks are also made available at the operational level. The objective at the operational level is to maximize profit through optimal allocation of cutblocks, taking into consideration market information on a monthly basis. The model is presented below.

Sets

242 T : set of time periods
 243 H : set of cutblocks
 244 S : set of silvicultural treatments
 245 E : set of harvest systems
 246 A : set of species
 247 M : set of mills

248 Parameters

250 V_{hsa} volume of species a available in cutblock h when subjected to silvicultural
 251 treatment s (m^3)
 252 N_a is the selling price per cubic meter of species a ($\$ \cdot m^{-3}$)
 253 C_e harvest cost under harvest system e ($\$ \cdot day^{-1}$)
 254 B_{hm} round trip distance from cutblock h to mill m (km)
 255 G_{hm} unit transportation cost between cutblock h and mill m ($\$ \cdot m^{-3} \cdot km^{-1}$)
 256 R_t maximum transportation capacity during period t (m^3)
 257 Y_{ha}^I initial roadside inventory of species a in cutblock h (m^3)
 258 Y_{th}^C unit stocking cost in cutblock h during period t ($\$ \cdot m^{-3}$)
 259 P_{se} is the productivity of harvest system e under silvicultural treatment s ($m^3 \cdot day^{-1}$)
 260 O_{te} number of work days available for harvest system e during period t
 261 D_{tam} is the volume of species a demanded by mill m during period t (m^3)
 262 AAC_a is the maximum harvestable volume of species a , set at the strategic level
 263 V is a very small number

264 Decision Variables

266 b_{hse} 1, if cutblock h is planned for harvest in any period using silvicultural treatment s
 267 and harvest system e , 0, otherwise
 268 x_{thse} is the proportion of cutblock h cut in period t under silvicultural treatment s using
 269 system e
 270 q_{tham} is the volume of species a transported from cutblock h to mill m in period t (m^3)
 271 y_{tha} is the volume of species a stored in cutblock h at the end of period t (m^3)
 272
 273

274 Objective Function

[11] Maximize Profit

$$\begin{aligned}
 &= \sum_{t \in T} \sum_{h \in H} \sum_{a \in A} \sum_{m \in M} q_{tham} N_a \\
 &- \sum_{t \in T} \sum_{h \in H} \sum_{s \in S} \sum_{e \in E} \sum_{a \in A} x_{thse} V_{hsa} C_e P_{se}^{-1} \\
 &- \sum_{t \in T} \sum_{h \in H} \sum_{a \in A} \sum_{m \in M} q_{tham} G_{hm} B_{hm} - \sum_{t \in T} \sum_{h \in H} \sum_{a \in A} y_{tha} Y_{th}^C
 \end{aligned}$$

275 Subject to,

$$[12] \quad y_{t,h,a} = Y_{ha}^I + \sum_{s \in S} \sum_{e \in E} x_{t,h,s,e} V_{hsa} - \sum_{m \in M} q_{tham} \quad \forall h, a, t = 1$$

$$[13] \quad y_{tha} = \sum_{s \in S} \sum_{e \in E} x_{thse} V_{hsa} + y_{t-1,h,a} - \sum_{m \in M} q_{tham} \quad \forall h, a, t > 1$$

$$[14] \quad \sum_{h \in H} q_{tham} \leq D_{tam} \quad \forall t, a, m$$

$$[15] \quad \sum_{h \in H} \sum_{s \in S} \sum_{a \in A} V_{hsa} x_{thse} \leq \sum_{s \in S} P_{se} O_{te} \quad \forall t, e$$

$$[16] \quad \sum_{t \in T} \sum_{e \in E} x_{thse} \leq 1 \quad \forall h, s$$

$$[17] \quad \sum_{s \in S} \sum_{e \in E} b_{hse} \leq 1 \quad \forall h$$

$$[18] \quad b_{hse} V \leq \sum_{t \in T} x_{thse} \quad \forall h, s, e$$

$$[19] \quad b_{hse} \geq \sum_{t \in T} x_{thse} \quad \forall h, s, e$$

$$[20] \quad \sum_{t \in T} \sum_{s \in S} \sum_{e \in E} x_{thse} = \sum_{s \in S} \sum_{e \in E} b_{hse} \quad \forall h$$

$$[21] \quad \sum_{h \in H} \sum_{a \in A} \sum_{m \in M} q_{tham} \leq R_t \quad \forall t$$

$$[22] \quad \sum_{h \in H} \sum_{s \in S} \sum_{e \in E} \sum_{t \in T} x_{thse} V_{hsa} \leq AAC_a \quad \forall a$$

$$[23] \quad x_{thse}, q_{tham}, y_{tha} \geq 0 \quad \forall t, h, s, e, a, m$$

276 The objective function (equation 11) aims at maximizing profit. Revenue is
 277 generated through delivery of volumes per species from cutblocks to mills. Costs
 278 include harvesting cost, transportation cost and inventory cost. Inventory cost

incorporates the carrying cost, ordering cost, backlog cost, deterioration cost and opportunity cost. Flow conservation constraints (equations 12 and 13) maintain balance of harvested volumes. Volumes transported to a mill in each period is constrained to be less than or equal to the demanded volume by species (equation 14). Volume harvested per period is less than or equal to the maximum logging production capacity (equation 15). It is assumed that the stand parameters are uniform in all cutblocks. The total volume harvested in a cutblock in all periods is less than or equal to the maximum volume available for a selected silvicultural treatment (equation 16), and the same treatment is applied even if harvesting is partitioned to multiple periods (equation 17). Equations 18 and 19 ensure that the variable b_{hse} attains a value of 1 even if a block is partially harvested. All volumes available must be procured over the planning horizon if a cutblock is selected for harvest (equation 20). Transportation capacity constraints are established through equation 21. Equation 22 restricts the total volume harvested of each species to the limits set at the strategic level. Finally, non-negativity restrictions are assigned to respective variables using equations 23. The mixed integer programming model is coded in AMPL® modeling language (Fourer et al. 2003) and solved using CPLEX® 12.5. Once operational level plans are implemented, the inventory is updated to account for the volumes harvested. Next, the strategic level model is again executed and the AAC is recorded to examine the impact on long-term wood supply.

3. A CASE STUDY

The system was applied to a forest management unit covering an area of 897,048 ha in the Nord-du-Québec region in Quebec, Canada. The initial state of the forest and pertinent land base information were obtained from the Quebec Ministry of Forests, Wildlife and Parks. The database also contained information on admissibility criteria for silvicultural treatments, growth and yield models, and transition rules defined by the Ministry as per BFC (2013) and "*le Guide Sylvicole du Québec*" (Larouche et al. 2013). The initial age class distribution by area is shown in Figure 3. The forest is dominated by mature and over-mature spruce-fir. Softwood species represented approximately 90% of the total volume in the forest, and hardwood species represented approximately 10%. The model was implemented in a sequential manner as it is the current practice in Quebec. The horizon of the strategic plan was set to 150 years divided into 30 periods of 5 years. There were 170 stand types each with different minimum harvest age. The maximum percentage deviation in harvest volume between subsequent periods was set to 5%. SilviLab generated approximately 13,000 variables in determining the annual allowable cut.

For the purpose of tactical planning, a grid with a cell size of 800m by 800m was superimposed on the map of the land base in SilviLab. Each cell was then treated as a cutblock; a total of 11,470 cutblocks were generated. Next, a query was made in SilviLab to retrieve a list of cutblocks with volumes eligible for harvest in the upcoming 5-year period. A minimum of 500 m³ of merchantable volume was required for a cutblock to be eligible for harvest. The volumes were categorised into four species groups: spruce/pine/fir, paper birch, poplar and other hardwood species. The data

contained information on volumes available by species under different treatments, and adjacent cutblocks. The tactical planning model was subsequently used to make a spatial plan for five 1-year periods.

The output from the tactical planning process was input into the operational planning model. The output data included: (i) a list of cutblocks available for harvest in the next five 1-year periods, (ii) silvicultural treatments prescribed to each of the cutblocks, (iii) non-prescribed alternative silvicultural treatments, (iv) volumes (m^3) by species group, and (v) distance between cutblocks and customer mills (km). Monthly demand in terms of volume was assumed to be a random parameter with normal probability distribution with a standard deviation that is 40% of the base demand. The base demand was created using historical mill consumption pattern for eight different mills. The values for standard deviation were established based on studies by Childerhouse and Towill (2000), Zhang and Zhang (2007) and UN (2013). Upon execution of all the operational level plans, the forest inventory is updated to account for the volumes harvested. Next iteration of the entire process is subsequently executed. The simulation was carried out for a total of 100 years (20 periods).

3.2. Scenarios development and statistical analysis

Scenarios were developed based on the following two criteria and a summary of the scenarios are displayed in Table 1:

1. Silvicultural flexibility: This criterion determines whether the scenario in consideration is permitted to exercise operational level silvicultural flexibility or not. In scenarios where flexibility is not permitted, the operational level model is

forced to implement the prescriptions made at the tactical level. In scenarios where it is permitted, the treatment decision made at the tactical level is revised. List of alternative treatments are made available to the operational level model. Thereby, allowing a new choice to be made to better align supply with demand. The treatments were limited to clearcut (CC) and variable retention (VR). CC involves harvesting all merchantable volumes. VR is a less intensive treatment which leaves behind merchantable trees unharvested covering over 5% of the total area for ecological purposes.

2. Base demand: We evaluated the long-term impact under two different market conditions. The first represents a scenario with monthly demand for 100% of the first period AAC; the second represents a scenario with monthly demand for only 60% of the first period AAC. The demand levels are reflective of the consumption levels by companies in many Canadian jurisdictions between 2001 and 2011 (NRC 2013).

Wilcoxon Signed Rank Tests were carried out in SigmaPlot 12.0 to test the null hypothesis of no significant difference in annual allowable cut, profit and area treated due to operational level silvicultural flexibility. Separate tests were carried out for each base demand levels, with annual allowable cut (m^3), profit values (\$) and area treated (ha) as the dependent variables, and silvicultural flexibility as the independent variable. Thus, tests were carried out for scenario 1 vs scenario 2 (base demand set at 100% of the initial AAC), and scenario 3 vs scenario 4 (base demand set at 60% of the initial AAC).

4. RESULTS

Wood procurement system profits under the different scenarios across a 20 period horizon are displayed in Figure 4. Fluctuation in profit was greater in scenarios 1 & 2 than in scenarios 3 & 4; this can be attributed to the higher base demand in scenarios 1&2. Random demand values were generated as a certain percentage of the base demand. Therefore, the higher base demand leads to a greater fluctuation in the actual profit generated, although it may be equivalent in percentage terms. The average profit per period in scenario 1 was approximately 3.7% higher than in scenario 2. Similarly, average profit per period in scenario 3 was approximately 2% higher than in scenario 4. Statistical analysis showed that the differences in the profit values between scenarios 1 & 2, and scenarios 3 & 4 were significant ($p < 0.001$). Likewise, significantly higher demand fulfillment rates were observed when silvicultural flexibility was permitted. The average demand fulfillment rate over the simulated period under scenario 1 was approximately 80% as opposed to 76% in scenario 2 ($p < 0.05$). Demand fulfillment rate under scenario 3 was 83% as compared to 77% in scenario 4 ($p < 0.05$).

Figures 5 and 6 show the proportion of area harvested by silvicultural treatment under different scenarios. The ratio of VR:CC ranged from 10:80 (period 5 in scenario 2) to as high as 77:23 (period 2 in scenario 1). The fluctuation observed in the proportions are due to the random demand values. Similar trend can be observed in scenarios utilising the same demand values; scenarios 1 & 2 show a similar trend as well as scenarios 3 & 4. In scenario 2 (Figure 5), these two treatments were applied to an equal number of hectares (50% apiece on average over the 20 period horizon). With silvicultural flexibility permitted (scenario 1), the proportion diverged significantly

($p < 0.05$), favoring CC at 53% over VR at 47%. In scenario 4 (Figure 6), without silvicultural flexibility, the proportion of area treated with CC (49%) was on average lower than that of VR (51%) but not statistically different. Permitting silvicultural flexibility (scenario 3) did not lead to a statistical difference, but there was slight increase in the application of CC (52%). In terms of the total area, permitting silvicultural flexibility led to a much lower number of hectares treated in all of the scenarios ($p < 0.001$). Approximately 6% more area was harvested in scenario 2 (no flexibility permitted) in comparison to scenario 1, and scenario 4 (no flexibility permitted) harvested 8.5% more area than in scenario 3.

Higher profits observed in scenarios with flexibility in silvicultural treatment was not unexpected considering that plans were permitted to be readjusted to the changing demand. Flexibility in silvicultural treatment leads to a better alignment between the assortments produced in the forest and demanded in the market. In this particular case, permitting flexibility led to a greater use of CC. From a wood procurement standpoint, CC is a more efficient treatment. With its application, higher volumes of wood can be procured from the same unit of area. Consequently, total area harvested was also lower in scenarios with flexibility permitted. This result is opposite to the findings reported in the Gautam et al. (2015) where permitting flexibility led to a greater use of partial harvest treatments. This can be attributed to the differences in forest composition in the two case studies. In contrast to the case presented in Gautam et al. (2015), the forest was much more homogeneous, with spruce/pine/fir representing approximately 90% of the total volume. Thus, there would have been rare instances of one assortment (with low demand in the market) restricting procurement of another assortment. In this case,

the model would have focused on higher volume yielding treatments to improve production efficiency. In the case of mixedwood forest, the model would likely have made greater use of partial treatments to produce the right mix of assortments demanded in the market.

The changes in AAC under different scenarios over the simulated time horizon are displayed in Figures 7 and 8. Comparable patterns can be observed in each of the scenarios. The AAC shows an increasing trend until the 8-9th periods, then a slight decline till the end of the horizon. In comparing scenario 1 and 2, the AAC is slightly higher for scenario 1 in periods 5, 6, 7, 8, 13 and 14, but lower in periods 15, 16, 17, 18 and 20. In making a similar comparison between scenarios 3 and 4, the AAC is higher in periods 4-8, but remains lower for the remainder of the periods. Statistical analyses did not demonstrate significant differences in the AAC values neither between scenarios 1 & 2, nor between scenarios 3 & 4.

The lack of significant difference in AAC can be attributed to the fact that silvicultural options were limited to two relatively similar treatments, CC and VR. Switching between CC and VR would not have had as much of an impact as compared to a change from CC to other partial cut treatments. Although we reject the null hypothesis of significant impact on AAC in this case, an experiment in a more heterogeneous forest could yield a different conclusion. In a more heterogeneous forest, as presented in Gautam et al. (2015), the operational level model would make use of wider array of silvicultural treatments. The accumulation of changes to considerably different treatments could ultimately lead to a significant impact on the AAC.

The total harvest level is another factor that would have contributed to the lack of significant impact on AAC. Harvest levels were below the allowable cut in all the scenarios. Thus, even though permitting flexibility led to utilisation of a more intensive treatment, the build-up of inventory may have mitigated the impact of choosing alternative silvicultural treatments. Furthermore, it was earlier speculated that, if the harvest level is well below the AAC, the incremental change induced by altering silvicultural treatment may be negligible, and if it is close to the AAC, impact will be greater. However, our experiment does not support this claim. The extent of the impact on the AAC was not noticeably different between scenarios that harvested closer to AAC (scenarios 1 & 2) and much lower than the AAC (scenarios 3 & 4).

5. DISCUSSION

The proposed system has proved to be an useful tool for making comparison of the long-term AAC between scenarios where operational level silvicultural flexibility is permitted and where it is prohibited. The implementation of the proposed system in other applications may necessitate adjustments. As an example, in practice, cutblocks are formed through combining a number of forest stands that are similar in terms of species composition and age. This is generally a manual procedure carried out using mapping software. Since our simulation was carried out for a 100-year horizon, manually generating cutblocks was not a practical option. Thus, a grid based method was used to develop cutblocks. Nevertheless, indiscriminately superimposing a grid over the land base led to formation of heterogeneous cutblocks. As a result, some cutblocks contained very little volume; these would have been economically infeasible to be harvested (Greene et al. 1997). However, it must be stated that this would have

influenced both scenarios, with and without flexibility in silvicultural treatment. Thus, it was deemed appropriate for our purpose, where the focus was on the differences between the scenarios. Continuing on with the discussion on cutblocks, they can be clustered to minimize operations cost (Mathey et al. 2008). Clustering minimizes the spread of cutblocks across the forest thus common roads can be used to transport wood from several cutblocks. As a result, road construction and maintenance costs are reduced. However, we did not take into consideration road building costs. Similarly, transportation costs were based on round trip distances between mills and blocks. In reality, a more efficient vehicle routing could be scheduled. The objective of anticipating the impact of silvicultural flexibility could be achieved without considering such costs, as long as it was kept constant in all scenarios being compared. There are a number of approaches proposed in the literature that allow incorporation of such decisions but it adds significant complexity to the model (Öhman and Lämås 2003; Smaltschinski et al. 2012).

Interoperability between models was attained through using volume (m^3) by species as the input and output at each hierarchy of the planning system. Although the approach is capable of representing the divergent process typical of the wood procurement system, it may not be adequate in all instances. In the presented case study, the demand from each mill was assumed to be a specified volume of particular species. Thus, raw materials in a cutblock could be diverted to different mills based simply on species. However, a single tree can be processed to different segments and be sent to separate mills to maximise value. Simulating such divergent process requires the bucking model to be included in the proposed planning system. Such models can be

used to seek optimal decisions on log bucking according to the specifications provided by the customer mills (Murphy 2008). Approaches to incorporate these algorithms will however significantly increase the complexity of the system in addition to commanding greater computational power. Thus, refinements should be based on the intended application of the system.

With respect to the plan development strategy, there is a growing interest towards developing an integrated approach as sequential method can lead to discrepancies between hierarchical plans (Rouillard and Moore 2009). Theoretically, integrated approach can increase consistency between different hierarchies and generate greater value, but the models become complex, and a practical size problem remains to be solved (McNaughton et al. 2000; Andersson and Eriksson 2007). Nonetheless, advent in technology has allowed greater degree of integration. As an example, now with the growing computation power, realistic sized strategic problems can be solved taking into consideration spatial aspects (Martin et al. 2016). However, the objective in this study was to simulate the conventional management practices. Sequential modelling approach reflects the current practice in the case study jurisdiction (BFC 2013). It is also the most common approach adopted in other jurisdictions and described in forestry textbooks (Gunn 2009; Bettinger et al. 2010). Furthermore, the plans of the different hierarchies are developed by separate groups. Thus, our proposed framework serves to better integrate different hierarchical plans.

Continuing on with the discussion on modeling approaches, it could be argued that discounting needs to be a part of the proposed planning system to account for time value of money. Although maximizing net present value is a common objective function,

the focus of this study was to investigate the impact of operational level silvicultural flexibility on long-term wood supply. As such, the objective function of the strategic model was set as volume maximization, similar to model II, form VI in Johnson Scheurman (1977) and Armstrong (2004). It is also the approach used to determine the annual allowable cut in the case study forest by the government (BFC 2013). At the operational level, nominal value could be used because comparison of profits between scenarios were made only at the same periods.

6. CONCLUSION

This paper presents a planning system to simulate the development and execution of hierarchical forest management plans with an objective to anticipate the impact of operational level silvicultural flexibility on long-term wood supply. It was hypothesized that operational level silvicultural flexibility improves profits but has a significant impact on the long-term AAC. The proposed system was implemented to a case study to test the hypotheses. The experiment did demonstrate a statistically significant improvement in profit for wood procurement systems as a result of permitting silvicultural flexibility at the operational level. In terms of the long-term impact of silvicultural flexibility on AAC, significant impact was not observed in this particular case; however, this finding should not be generalized. The outcome will certainly vary based on forest types and options available on silvicultural treatments. Nevertheless, the proposed system can help forest planners and supply chain managers better integrate their respective needs. For supply chain managers, this translates into more precise product deliveries. For forest planners, this means the ability to foresee the impact of short-term decisions on long-term wood supply. The proposed system could be further refined for its implementation

to other applications. However, the extent of these refinements should be based on the intended use as it will increase the complexity of the system.

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Tables

Table 1. A list of scenarios developed for the experiment

Scenario	Silvicultural flexibility	Base demand (% of allocation)
1	Yes	100
2	No	100
3	Yes	60
4	No	60

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Figure Captions

- Figure 1. The overall plan development and implementation strategy in the proposed planning system.
- Figure 2. Flowchart of the Monte Carlo integer programming procedure.
- Figure 3. The initial age class structure of the case study forest. Each age class represents a 5-year interval.
- Figure 4. The total profit values yielded under different scenarios per period.
- Figure 5. Proportions of silvicultural treatments applied under scenarios 1 and 2.
- Figure 6. Proportions of silvicultural treatments applied under scenario 3 and 4.
- Figure 7. Comparison of annual allowable cut under scenarios 1 and 2.
- Figure 8. Comparison of annual allowable cut under scenarios 3 and 4.

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