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Examining the Long-Term Impact of Operational Level Silvicultural Flexibility in a Hierarchical Planning Framework: A Simulation-Optimization Based Approach

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Abstract. Flexibility in the choice of silvicultural treatments at the operational level has been identified as a possible way to mitigate the impact of uncertain supply and demand on supply chain performance. However, its influence on long-term wood supply has not yet been investigated. This study examines the impact of such flexibility on supply chain benefits and long-term wood supply. A simulation-optimization framework for hierarchical forest management planning was first set up. Mathematical models were formulated to optimize plans at different hierarchies, i.e. strategic, tactical and operational. In the architecture, the strategic model is first solved to determine the annual allowable cut (AAC) in SilviLab, a modelling platform developed by FORAC research consortium for forest growth simulation and optimization. Next, the tactical model allocates cutblocks to five 1-year periods, also prescribing silvicultural treatments. The subsequent operational level model generates monthly plans in a rolling planning horizon basis to satisfy prevailing market demand. Upon execution of all operational level plans for the five years, the land base inventory is updated and the AAC is re-calculated. Execution of this procedure was simulated for 100 years using dataset from a management unit in Quebec, Canada. Scenarios, with and without operational level silvicultural flexibility, were experimented. In scenarios with flexibility, profit improvements of 2-3.7% were observed without significant difference in the AAC over the simulated time horizon.

Keywords: Agility, flexibility, wood procurement, silviculture, SilviLab, forest management, Monte-Carlo integer programming, timber supply.

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1. Introduction

Forest management planning is an important task that governs the value adding capacity of the dependent stakeholders. These stakeholders include industries, Aboriginal peoples, local communities, etc. with unique ways in which forests are valued. Developing a plan deemed optimal presents a complex challenge due to the stochastic and dynamic nature of the forest systems, social constructs and economic parameters. Furthermore, the credibility of the developed plan hinges not on the optimality of the plan, but rather on the closeness of the executed activities to what was planned (Gunn 2009; Paradis et al. 2013). The problem is exacerbated by imprecise knowledge of inventory. In this context, it is important to devise a credible plan and permit flexibility to readjust plans to improve convergence between the planned and executed activities. Such an approach generates value adding opportunity also for wood procurement systems (WPS) through improved agility to satisfy supply chain's timber demand. Flexible harvest policies as described in Brazee and Mendelsohn (1988) and Knoke and Wurm (2006) could be employed instead of flexibility. However, it would require formulation of a new plan through consultation with stakeholders, construction of access roads, and other preparatory tasks. Thus, the response time required for the process renders the option impractical from an agility perspective.

Agility implies the ability to respond promptly and effectively to unexpected short-term fluctuations in demand (Gautam et al. 2013). One possible way to improve WPS agility is through flexibility on the choice of silvicultural treatments at the operational level instead of fixing the decision at an upper hierarchy. Practitioners could be provided with an array of ecologically feasible silvicultural treatments for a cutblock from which a selection can be made to satisfy market demand. Such a practice allows better alignment of supply with the prevailing demand considering that silvicultural treatments dictate the array of assortments and their quantities produced from cutblocks. Lussier (2009) demonstrated an improvement in supply chain profit through flexibility in tree choice within a partial harvest system. Gautam et al. (2014) quantified the value adding potential through allowing flexibility in the choice of silvicultural treatment itself at the operational level.

Exercising silvicultural flexibility entails postponing the final decision-making rights to the operational level. Postponement has been identified as an effective strategy to improve supply chain agility (Christopher 2000). However, considering that forest management planning is carried out using a top-down hierarchical approach, it leads to a situation of distributed decision making as described in Schneeweiss (2003). Hierarchical approach is adopted 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 other ecological and social concerns. The outcome of the plan is the determination of annual allowable cut (AAC). Subsequently, a tactical plan spatially disaggregates the volume targets incorporating additional ecological and social constraints. The process results in generation of cutblocks along with a silvicultural treatment prescription for each. The silvicultural treatments are prescribed ensuring that the total volume harvested in the forest will be within a target range set at the strategic level. Further down the hierarchy, operational plans outline schedules and specific plans of action to meet industrial demand for timber (D'Amours et al. 2008). Therefore, AAC could be impacted when silvicultural treatments are altered at the operational level, despite the ecological suitability of the applied treatment. Thus, amendment in the operational level plan has to be evaluated in terms of its impact on the AAC. A coordination mechanism is required to make such an evaluation.

A number of studies have proposed iterative procedures to ensure inter-level consistency. Weintraub and Cholaky (1991) present a manual approach to improve consistency between strategic and tactical planning levels. At the strategic level, the forest is divided into smaller zones and aggregated information is used to reduce the size of the problem. Decision variables in the strategic model include determination of harvest levels at each zone and road building schedule. The outcome of the strategic model provides directives for the tactical model in terms of timber production goals as well as road building budget. The tactical level model then aims to maximize profit using disaggregated information under constraints imposed by the strategic level plan. If there is a lack of consistency between the two levels, adjustments are made at both levels and a second iteration of the process is then conducted. In Nelson et al. (1991), a long-term strata based model is first used to determine the volume targets for 15 decades. Subsequently, Monte Carlo integer programming technique is used to solve spatial harvest scheduling problem with adjacency constraints for the first three decades. In the bottom up phase, the long-term plan is 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) propose a method to simultaneously consider strategic and tactical planning. First, aggregation of forest stands is done through a cluster analysis technique to form macro stands. A strategic plan for a 45 year horizon is then developed to set volume targets and decide on plant locations. The plan is disaggregated at the tactical phase where decision on roads to be built, cutblocks to be harvested, and volumes to be transported from cutblocks to mills are made. The extent of discrepancy in harvest and road cost between the two levels is then measured. If deemed unacceptable, further iterations are run re-aggregating the first period solution at a lower degree until an acceptable strategic-tactical solution is attained. Beaudoin et al. (2008) use an anticipative approach to ensure feasibility of tactical plan at the operational level. At the tactical level, a number of candidate plans are generated with decisions on harvesting, transportation and inventory. The operational level logistical costs associated with the developed plans are 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) is influenced by the anticipated information, eliminating plans that would be infeasible at the operational level. A similar concept was applied in Marinescu and Maness (2010) who propose an algorithm that links models to support decision making at different hierarchies, between a multi-criteria timber allocation model and a sawmill optimization model. The algorithm allows iterative negotiation between the models to maximize value at both levels. The impact of allowing flexibility in the choice of silvicultural treatment at the operational level on long-term wood supply has not yet been conducted to our knowledge.

The overall aim of the study is therefore to examine the impact of operational level silvicultural flexibility on long-term wood supply sustainability. The specific objectives are: (i) to develop a mechanism to simulate the development and execution of plans at different forest management planning hierarchies; (ii) quantify the impact of operational level silvicultural flexibility on long-term annual allowable cut (AAC); and (iii) conduct a value-added assessment of operational level silvicultural flexibility. The next section provides a description of the method used in the study. First, the simulation-optimization mechanism for implementing the hierarchical planning process is described followed by a description of the case study. The results of the experiment are presented in Section 3. Finally a brief conclusion and recommendations for future investigations are provided in section 4.

2. Method

A framework was developed to simulate iterative planning and execution of hierarchical plans in a forest land base. The process is depicted in Figure 1. First, a strategic model is used to determine the AAC for a time horizon of 150 years. Next, a tactical model spatially identifies cutblocks to be harvested while respecting the AAC. As such, the strategic and tactical plans are developed from a government or land owner's perspective, with a goal of sustaining long-term wood supply. The output of the tactical phase consists of five annual plans with a list of cutblocks allocated for each year and a silvicultural treatment prescribed to each cutblock. At the operational level, the annual plans are optimized to develop monthly schedules to meet the prevailing demand in a rolling planning horizon basis. The operational level plans are developed from the perspective of a wood supplier attempting to maximize economic value. This process of development and implementation of plans in different hierarchies is depicted in Figure 2.

Once all operational level plans are implemented, the land base inventory is updated followed by subsequent iterations of the process as displayed in Figure 1. At each iteration of this simulation-optimization process, fluctuation in annual allowable cut and WPS' profits were recorded. The upcoming sub-sections provide a description of the models used in each of the planning hierarchy.

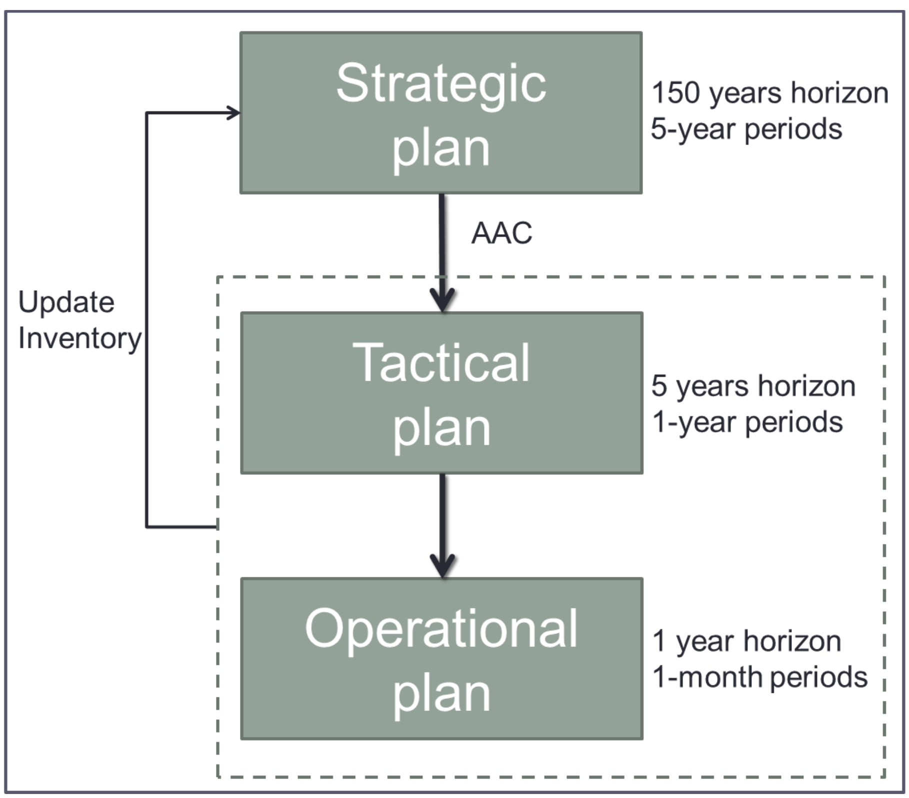

Figure 1. An overview of the hierarchical planning process simulation.

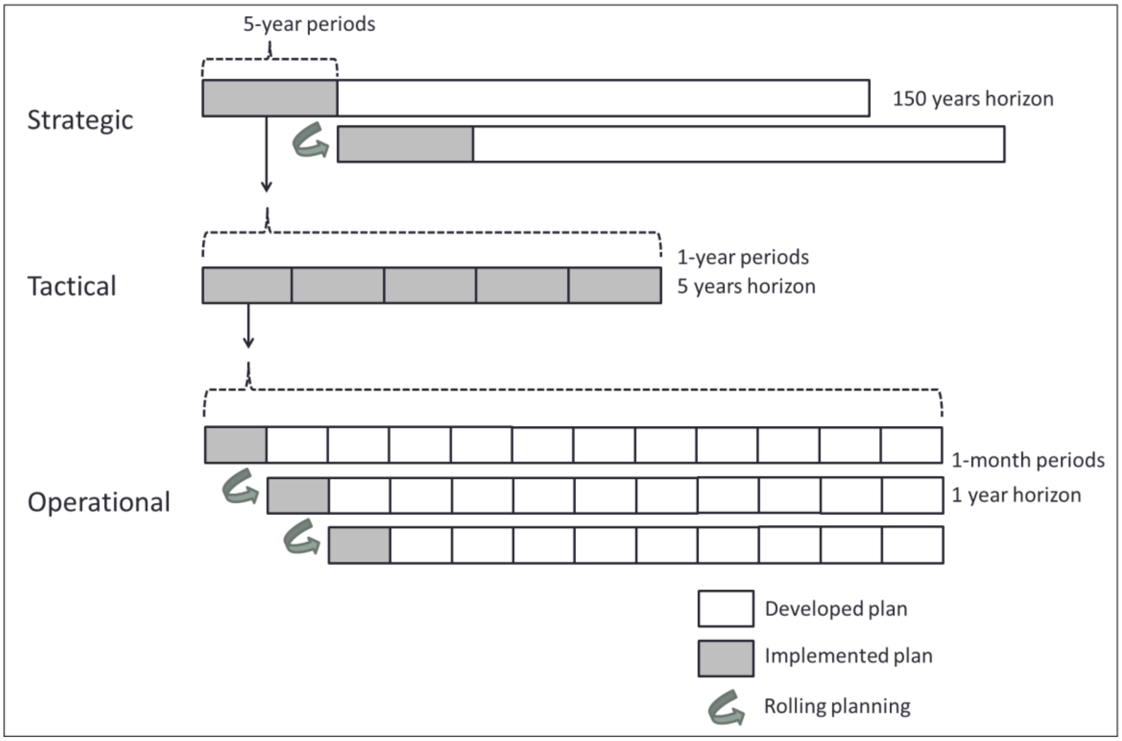

Figure 2. The overall plan development and implementation strategy in the experiment

2.1. Hierarchical planning models

The strategic 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. The objective (Equation 1) of the model is to maximize volume harvest over thirty 5-year periods. The objective (equation 1) of the model is to maximize volume harvest over thirty 5-year periods. h_t represents the total volume harvested (m^3) in period t. N is the number of periods in the planning horizon.

[1] $$\text{Maximize Volume harvest} = = \sum_{t=1}^{N} h_t$$

The constraints include: (i) area accounting constraints (ii) even flow constraint to limit periodic harvested volume fluctuation to within 5%, and, (iii) Non-negativity constraints.

The tactical model minimizes volume allocation to each of the time periods while meeting volume targets set at the strategic level. It is assumed that the cutblocks eligible for harvest in the 5-year period have been delineated and the data is available. The objective of the model is to minimize the total volume harvested (Equation 2) of assortment *a* from cutblock *h* using silvicultural treatment *s* in period *t*. Equation 3 forces the model to meet volumes targets set by the strategic model. Equation 4 ensures that only one silvicultural treatment is applied to each of the selected cutblock. Equation 5 prohibits the harvesting of adjacent cutblocks until free-to-grow stage is attained. Finally, variable O_{hst} is constrained to be a binary variable (Equation 6).

Sets

T: is the set of time periods *t*
H: is the set of cutblocks *h*
S: is the set of silvicultural treatments *s*
A: is the set of species *a*

Input Data

V_{hsa} Volume of species *a* available in cutblock *h* when subjected to silvicultural treatment *s* (m^3).
N_h Set of adjacent cutblocks.
$\nexists_{sat}$ Volume target of species *a* in period *t* under silvicultural treatment *s*.

Decision Variables

$$O_{hst} \begin{cases} 1, \text{ if cutblock } h \text{ is allocated for harvest under silvicultural treatment } s \text{ in period t.} \\ 0, \text{ otherwise} \end{cases}$$

Objective Function

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

Subject to:

[3] $$\sum_h V_{hsa}\, O_{hst} \geq \nexists_{sat} \;\; \forall\, s, a, t$$

[4] $$\sum_s \sum_t O_{hst} \leq 1 \;\; \forall\;\, h$$

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

[6] $$O_{hst} \;\in \{0,1\}$$

The output of the tactical plan is a list of cutblocks to be cut with a silvicultural treatment prescribed to each cutblock. The objective at the operational level is to optimally allocate these cutblocks taking into consideration market information on a monthly basis. The operational model is adopted from Gautam et al. (2014) with two changes: (i) cost imposed in association with altering silvicultural treatment was removed from the objective function. The cost is no longer required since long-term impacts are simulated in this study. (ii) Market transaction unit was changed from assortments to species to allow interoperability between different hierarchical models. The model is presented below.

Sets

T: is the set of time periods *t*
H: is the set of cutblocks *h*
S: is the set of silvicultural treatments *s*
E: is the set of harvest systems *e*
A: is the set of species *a*
M: is the set of mills *m*

Input Data

V_{hsa} maximum volume of species *a* available in cutblock *h* when subjected to silvicultural treatment *s* (m^3)
N_a is the selling price per cubic meter of species *a* ($\$\cdot m^{-3}$)
C_e harvest cost under harvest system *e* ($\$\cdot day^{-1}$)
B_{hm} round trip distance from cutblock *h* to mill *m* (km)
G_{hm} unit transportation cost between cutblock *h* and mill *m* ($\$\cdot m^{-3}\cdot km^{-1}$)
R_t maximum transportation capacity during period *t* (m^3)
Y^I_{ha} initial roadside inventory of species *a* in cutblock *h* (m^3)
Y^C_{th} unit stocking cost in cutblock *h* during period *t* ($\$\cdot m^{-3}$)
P_{se} is the productivity of harvest system *e* under silvicultural treatment *s* ($m^3\cdot day^{-1}$)
O_{te} number of work days available for harvest system *e* during period *t*
D_{tam} is the volume of species *a* demanded by mill *m* during period *t* (m^3)

Decision Variables

b_{hse} = 1, if cutblock *h* is planned for harvest in any period using silvicultural treatment *s* and harvest system *e*; 0, otherwise

x_{thse} is the proportion of cutblock *h* cut in period *t* under silvicultural treatment *s* using system *e*

q_{tham} is the volume of species *a* transported from cutblock *h* to mill *m* in period *t* (m^3)

y_{tha} is the volume of species *a* stored in cutblock *h* at the end of period *t* (m^3)

Objective Function

[7] $$\text{Maximize Profit} = \sum_{t\in T}\sum_{h\in H}\sum_{a\in A}\sum_{m\in M} q_{tham}N_a - \sum_{t\in T}\sum_{h\in H}\sum_{s\in S}\sum_{e\in E}\sum_{a\in A} x_{thse}V_{hsa}C_eP_{se}^{-1} - \sum_{t\in T}\sum_{h\in H}\sum_{a\in A}\sum_{m\in M} q_{tham}G_{hm}B_{hm} - \sum_{t\in T}\sum_{h\in H}\sum_{a\in A} y_{tha}Y_{th}^{C}$$

Subject to:

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

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

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

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

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

[13] $\sum_{s\in S}\sum_{e\in E} b_{hse} \leq 1 \qquad \forall\; h$

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

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

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

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

[18] $b_{hse} \in \{0,1\}$

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

The objective function (equation 7) aims at maximizing profit. Revenue is generated through delivery of volumes per species from cutblocks to mills. Costs include harvesting cost, transportation cost and inventory cost. Flow conservation constraints (equations 8 and 9) 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 (equation 10). Volume harvested per period is less than or equal to the maximum production capacity (equation 11). 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 available under the selected silvicultural treatment (equation 12), and the same treatment is applied even if harvesting is partitioned to multiple periods (equation 13). A relationship between variables B_{hse} and X_{thse} is established through equation 14 and 15. All volumes available must be procured over the planning horizon if a cutblock is selected for harvest (equation 16). Transportation capacity constraints are established through Equation 17. Finally, binary restrictions and non-negativity restrictions are assigned to respective variables using equations 18 and 19.

2.2. Data Description & Experimentation

Strategic planning was carried out on a forest management unit in Quebec, Canada. The land base information was obtained from the Quebec Ministry of Forests, Wildlife and Parks. The database contained information on stand areas, initial forest resource inventory, growth and yield tables as well as the forest transition rules. A map of the land base is provided in Figure 3. A number of silvicultural options were made available for timber harvesting: commercial thinning, partial harvest, shelterwood cutting, variable retention and clearcut. The land base information along with the strategic planning model described earlier was input into SilviLab.

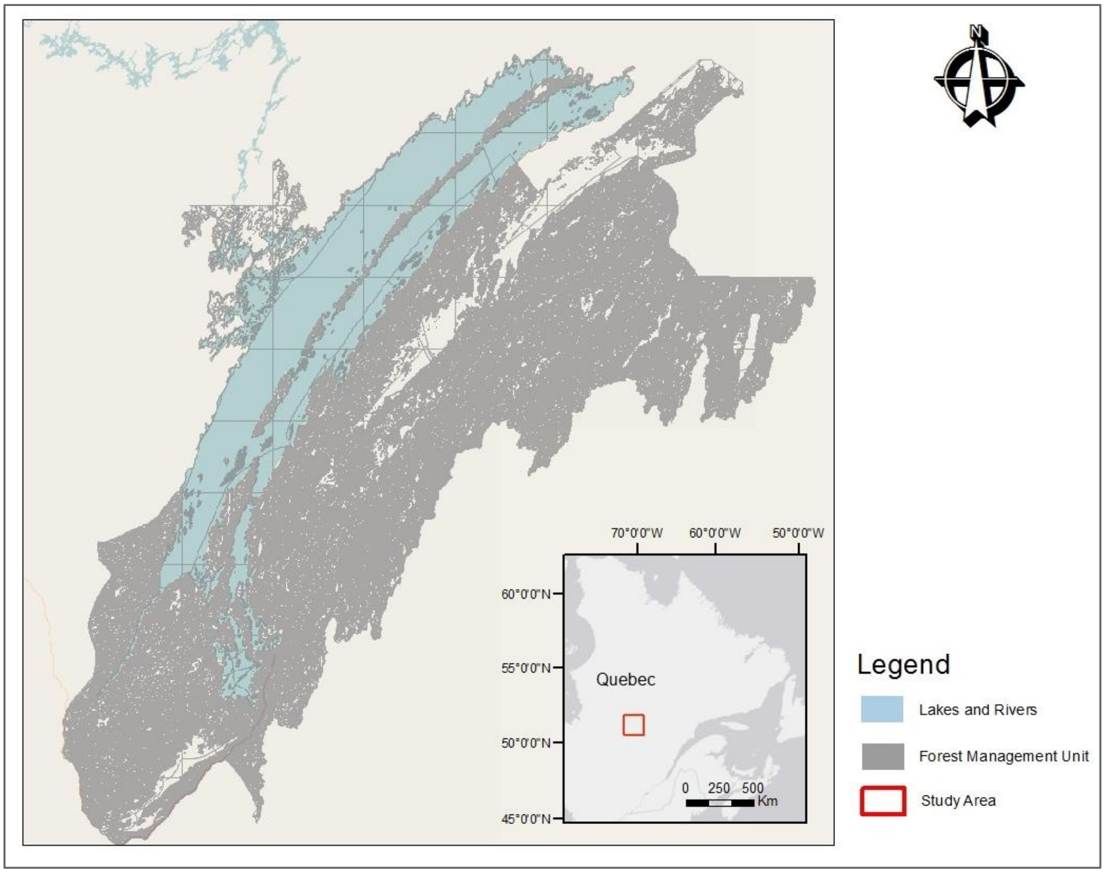

Figure 3. A map showing the study area in Quebec, Canada.

For the purpose of tactical planning, a grid with a cell size of 800m X 800m was superimposed on the map of the land base in SilviLab. Each cell was then recognized as a cutblock. A query was then made in SilviLab to retrieve a list of cutblocks with volumes eligible for harvest for the upcoming 5-year period. The list also included adjacency information. The tactical planning model described earlier was subsequently used to make a spatial plan for five 1-year periods. Due to the size of the problem, a heuristic technique, Monte Carlo integer programming, was used to attain a solution in a practical time frame. Monte Carlo integer programming is an algorithm to generate a plan through randomly selecting and adding cutblocks that respect the adjacency constraint until the volume targets are met (Boston and Bettinger 1999). Although the algorithm cannot guarantee the optimal solution, the time frame in which solutions are generated makes it a practical choice for carrying out the experiment. The flowchart in Figure 4 illustrates the technique. The method was executed in Microsoft Excel 2010 using Visual Basic for Applications (VBA).

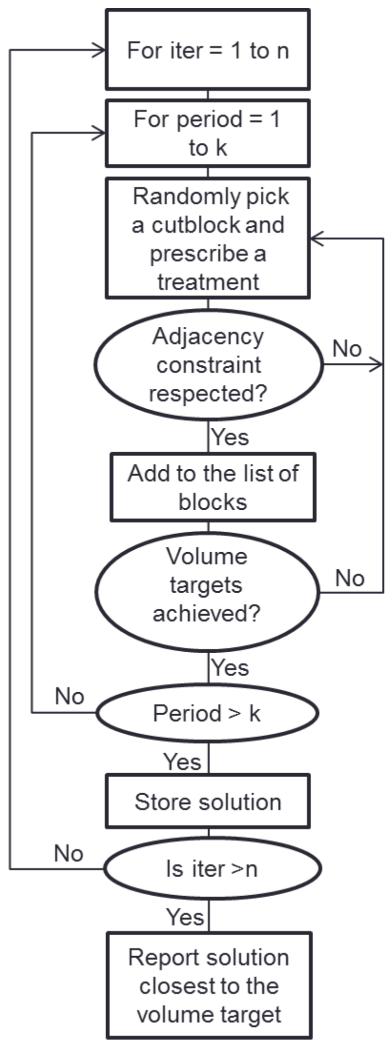

Figure 4. Flowchart of the Monte Carlo integer programming procedure.

The output of the tactical planning process was subsequently 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) the silvicultural treatment prescribed to it, (iii) non-prescribed but ecologically feasible silvicultural treatments, (iv) the volumes by species (m^3), and (v) distance between cutblocks and customer mills (km). Monthly demand was assumed to be a random parameter with normal probability distribution with a standard deviation that is 40% of the base demand. These values are based on studies by Childerhouse and Towill (2000), Zhang and Zhang (2007) and UN (2013). Base demand was generated using historical mill consumption pattern as described in Gautam et al. (2014). The selling price per cubic meter of each species group was obtained from Wood Producers Association of Quebec (SPFRQ 2014). Concerning harvesting systems, two options were made available: cut-to-length (CTL) and full-tree systems (FT). The productivity and cost values published in Gautam et al. (2014) were adopted for the experimentation. The operational mixed integer programming model was coded in AMPL modeling language and solved using CPLEX 12.5.

2.3. Scenarios development

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 operational level silvicultural flexibility or not. In scenarios where flexibility is not permitted, the operational level model is forced to implement the prescription made at the tactical level. In scenarios where it is permitted, the treatment decision made at the tactical level is reassessed. The same list of ecologically feasible treatments that was used at the tactical level is made available to the operational level model. Thus, allowing a new choice to be made to better align supply with demand.

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. Although the base demand was maintained at different percentage of the allocated volumes, it was still assumed to be a random parameter as indicated in the earlier section. The demand levels are reflective of the current consumption levels by companies in many jurisdictions (NRC 2013).

Table 1: Summary of the scenarios simulated in the experiment

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

2.4. Statistical analysis

Wilcoxon Signed Rank Tests were carried out in SigmaPlot 12.0 to test the null hypothesis of no significant difference in annual allowable cut and profit due to operational level silvicultural flexibility. Separate tests were carried out for each base demand levels with annual allowable cut (m^3) and profit values ($) as the dependent variable, and the 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).

3. Results and Discussion

Our results show that a significant improvement in profit can be achieved when operational level silvicultural flexibility is permitted. WPS profits under the various scenarios across a 20 period horizon are displayed in Figure 5; each period represents five years. Flexibility in the choice of silvicultural treatment at the operational level led to significant difference in profit values in all scenarios. In scenarios 1 & 2 (base demand set at 100% of the initial AAC), there was an average increase in profit of approximately 3.7% per 5-year period. Average profit increased by approximately 2% for scenarios 3 & 4 (base demand set at 60% of the initial AAC).

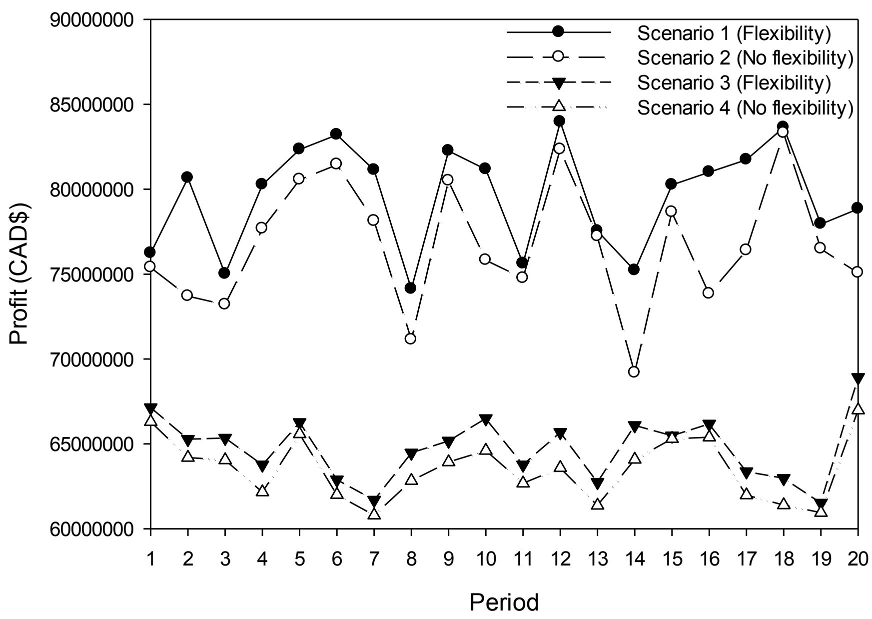

Figure 5. Profits values yielded under different scenarios.

The profit improvement observed in this study (2-3.7%) is a function of the type of the forest in which the study was conducted. The database used in this study originates from the boreal forest with predominantly softwood species (approximately

90%) with a low frequency of mixedwood stands. In regions with a higher frequency of mixedwood stands, operational level silvicultural flexiblity will offer a greater advantage. In mixedwood stands, alternative treatments will produce different mix of product assortments as opposed to just different proportions of the same products. The availability of different mix offers greater opportunity to better match supply with demand. Nevertheless, given the competitive pressures facing the industry, the profits reported here are quite substantial, especially given that they can be realised without any capital investment.

The AAC, demand, and harvested volumes in each period under different scenarios are displayed in Figures 6 to 9. The base demand was set up to be approximately 100% of the first period AAC in scenarios 1& 2 (Figures 6 & 7) and 60% of the first period AAC in scenarios 3 & 4 (Figures 8 & 9). The demand fulfillment rate over the simulated period under scenario 1 was approximately 80% as opposed to 76% in scenario 2. Similarly, the demand fulfillment rate under scenario 3 was 83% as compared to 77% in scenario 4. Thus flexibility in silvicultural treatment at the operational level led to an increase in demand fulfillment rates of 4% and 6% in the respective scenarios.

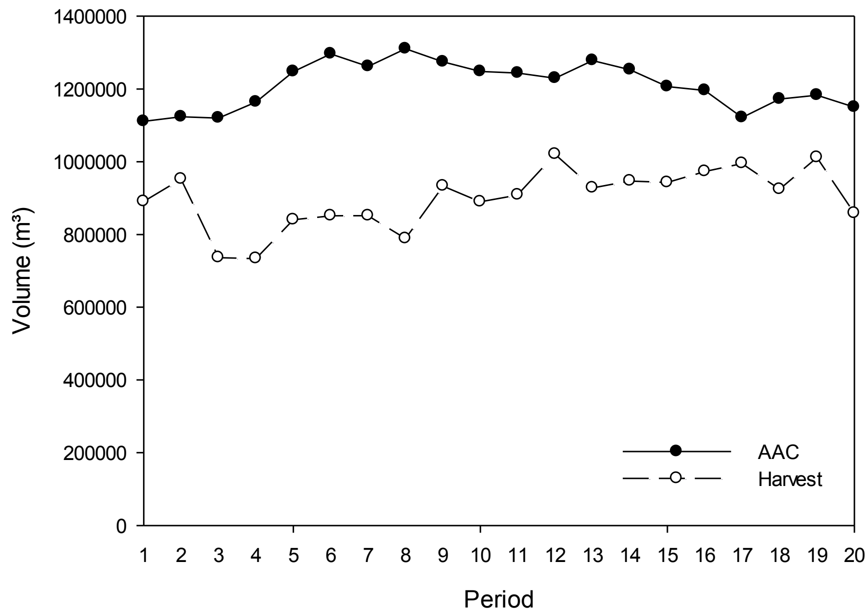

Figure 6. Illustration of the annual allowable cut (AAC), volumes demanded and harvested under scenario 1.

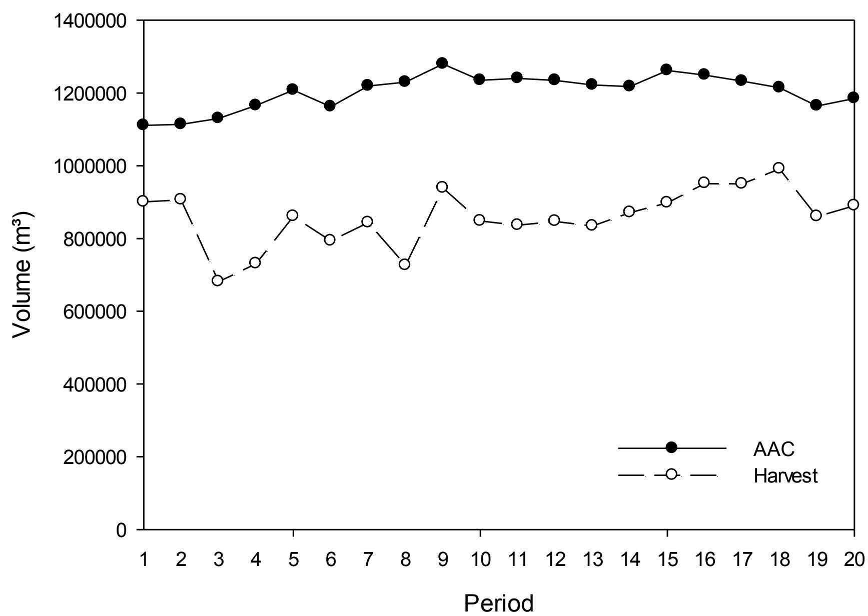

Figure 7. Illustration of the annual allowable cut (AAC), volumes demanded and harvested under scenario 2.

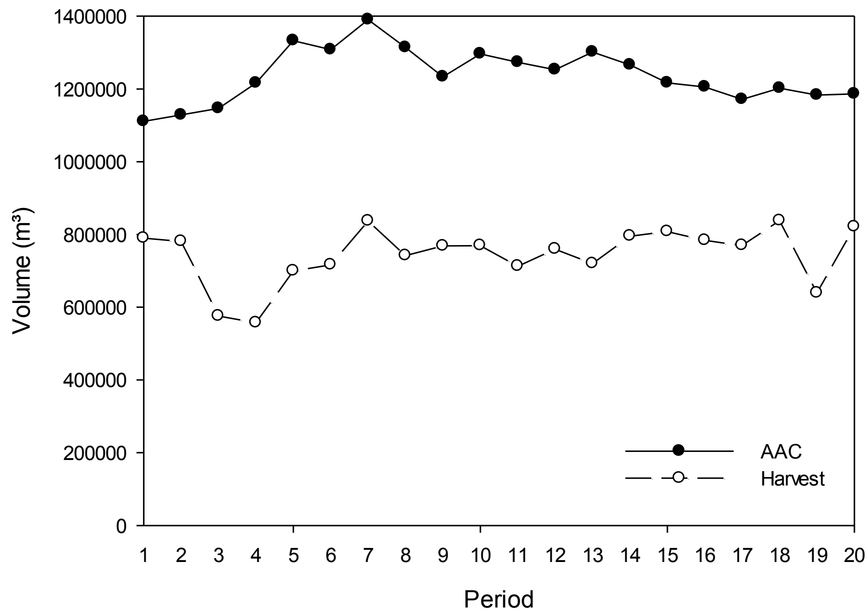

Figure 8. Illustration of the annual allowable cut (AAC), volumes demanded and harvested under scenario 3.

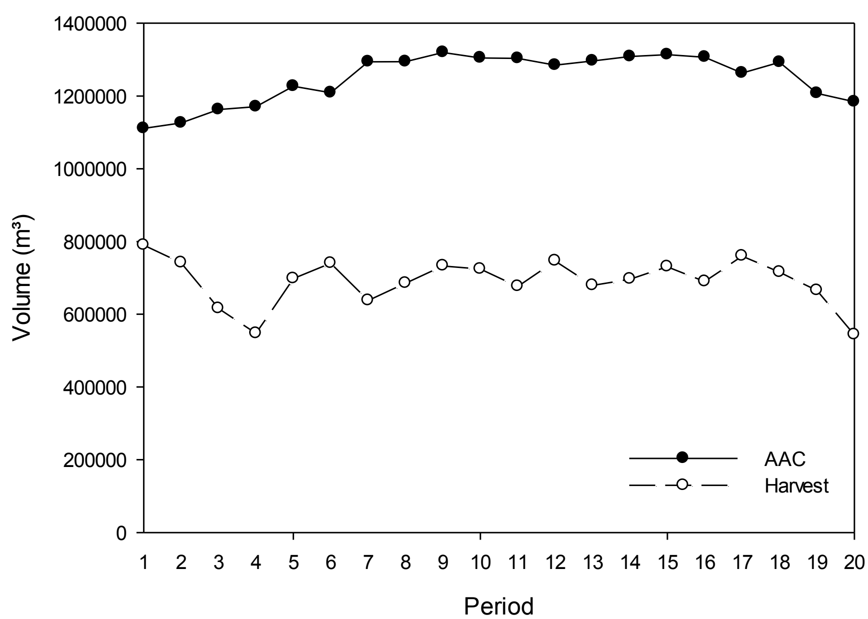

Figure 9. Illustration of the annual allowable cut (AAC), volumes demanded and harvested under scenario 4.

In terms of fluctuation in AAC over the simulated period, 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. Since the trend is observed in each of the scenarios, it is most likely due to the fact that the initial age class distribution in the land base was not normal (Armstrong 2004), and the subsequent harvest levels. Nevertheless, the objective of the investigation was to observe the impact of exercising operational level silvicultural flexibility on AAC. Neither of the statistical analysis demonstrated a statistical significant difference between the AAC trends under different scenarios. Therefore, operational level silivicultural flexibility did not have a significant impact on the AAC in this study.

The findings have implications for forest management policies. The Canadian public have generally shown a degree of distrust with the industry’s role in forest management (Nadeau et al. 2008; Yelle 2013). As such there has been a desire for a greater government control over forest operations. As an example, most recently in the province of Quebec, a new law came into effect (April 2013) shifting decision-making power from the industry to the provincial government (MRNF 2013). This replaces the timber supply and forest management agreements with timber supply guarantees. Under the previous regime, the forest companies were responsible for planning, harvesting and regeneration in the land base with the government overseeing the entire process. With the new regime in effect, the companies are guaranteed a right to purchase timber, but the government has taken over the role of planning and regeneration. Despite the policy changes, the economic challenges still remain. In fact, from company perspective, there is now an added uncertainty associated with wood supply. The planning horizon of forest operations is reduced to a shorter time period, thus, sacrificing potential savings associated with a longer and a more optimal plan. The problem of inaccurate inventory will further exacerbate the issue. The impact could be mitigated through developing policies that permit a greater flexibility in silvicultural treatment at the operational level. The incremental improvement in profit values reported in this report can dictate financial feasibility of the generated plans and continuation of mills.

Governments generally incorporate a requirement into the harvesting licence to maintain an even flow of timber (Mathey et al. 2009). An argument for such policy is that it maintains regional employment. However, maintaining an even flow of timber without consideration for market conditions will negatively impact supply chain performance as economic cycles and market shifts are overlooked (Krcmar et al 2008; Mathey et al. 2009). Such a regulatory policy could in fact lead to a consequence exactly opposite of what it was set out to achieve. If firms continue to operate under net loss, mills will eventually be shut down leading to loss of employments. A potential approach to alleviate the problem is through maintaining silvicultural flexibility at the operational level. Our result demonstrates that economically feasible harvest levels could be increased using the approach.

New forest management regimes based on ecosystem based management (EBM) principles are being adopted across Canada (McAfee and Malouin 2008; Gauthier et al. 2009). From a forest operations perspective, it implies development of a management strategy that prescribes a range of silvicultural treatments to mimic natural disturbance (Groot et al. 2004). As such, new silvicultural treatments are also being proposed (Raymond et al. 2009; Lussier and Meek 2014). With the new regime in Quebec, the proportion of these treatments are fixed in the annual plans, flexibility on these treatments are not explicitly discussed. There are multiple ways to achieve the goals set in the management strategy; fixing these decisions in the annual plan will certainly ensure that the targets are achieved but allowing flexibility could also achieve the stated goals as well as permit WPS to better align supply with demand. The benchmarking of silvicultural treatment proportions could be done over a longer time horizon.

Although our experiment clearly demonstrates the advantages of silvicultural flexibility without negative impact on wood supply, the results must be viewed in light of the assumptions made in the experiment. The generalizability of the results depends on the validity of the growth models and the transition rules in the particular region. Also, the results were obtained through simulating iterative planning and implementation over a 100 year time horizon. The results cannot be extrapolated to speculate on the impact of operational level silvicultural flexibility beyond the simulated time horizon. It is also assumed that prescribed silvicultural treatment will be accurately executed on the ground. The assumption is certainly attainable but greater operational control may be required.

The results must also be viewed in light of the methods adopted for carrying out the experiment. Modeling hierarchical management planning of an entire forest management unit and simulating its execution was a task with many components. Some of the modeling approaches used may have influenced the results of the analysis. For example, in the tactical model, a grid based system was used to develop cutblocks which is not realistic but it was practical approach to carry out the experiment. It will be important to continually refine the system to better represent the reality. The system will be a useful tool for management and also for research purposes. It can contribute towards developing a better understanding of the relationship between forest management and forest products supply chains and integrating their needs in the decision-making.

4. Conclusion

The objective of this study was to examine the impact of operational level silvicultural flexibility on long-term wood supply. The availability of Silvicultural options rendered the WPS more agile, allowing it to better match supply with demand, and resulting in significant profit improvement for the WPS. Our simulation-optimization experiment did not show a significant difference in the long-term wood supply as a result of exercising silvicultural flexibility over a 100-year time horizon. The generalizability of our results is limited by the simulation-optimization method employed, and the parameters used in the experiment. Nevertheless, the study demonstrates the value adding potential of the proposed approach for all stakeholders. The government receives higher stumpage revenue as a result of increased harvest level. Increasing harvest level closer to the annual allowable cut also provides greater credibility to the hierarchical forest management process. From a local community perspective, the incremental increase in profit could be the difference that justifies continued mill operation and value-creation.

Finally, for the industry, it allows them to maintain a competitive supply chain with a greater chance of success in the global market. Several jurisdictions across Canada are in the process of reforming their forest tenure systems with a goal of achieving sustainability. Thus this is an opportunity to reinvigorate forest sector competitiveness through introducing policies to provide agility to WPS that are essential for economic and social sustainability.

Future studies should focus on further refinement to the system proposed in this study. There is an opportunity to advance the technology in cutblock generation. A grid based system was used for the purpose of carrying out the experiments in this study; however, a system that can generate a more realistic cutblock would provide a more accurate future prediction. Algorithms need to be developed that can generate realistic cutblocks in a practical timeframe to allow such iterative simulation-optimization of the hierarchical forest management planning process. The system will prove to be a useful tool to gain insights on the relationship between forest management practices and supply chains.

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