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Integrating Silvicultural Decisions in Operational Level Wood Procurement Planning to Improve Forest Products Supply Chain Agility

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Abstract. Forest products industry's competitiveness is influenced by the agility of wood procurement systems in delivering raw material to support downstream manufacturing activities. However, silvicultural treatments are prescribed in forest management plans and set as constraints for supply chains managers, restricting supply flexibility. This study was conducted with an objective of quantifying the benefits of improving wood procurement systems agility through flexibility in the choice of silvicultural treatments at the operational level. The aim was also to determine the conditions under which the benefits from flexibility can be realized without impacting long-term supply. An experiment was designed to compare the benefits of flexibility on supply chain performance, profit and demand fulfillment. Future impact of exercising flexibility on long-term supply was accounted in a range of scenarios through incorporating costs associated with different intensities of silvicultural regimes. The scenarios were simulated using operational level data obtained from an industry case study, and solved using a mixed integer programming model. Scenarios with flexibility yielded significantly higher profits and demand fulfillment rates. The experiment demonstrated that under the status quo approach, without flexibility, supply chains are unable to improve demand fulfillment rates despite the existence of assortments in cutblocks.

Keywords: Silviculture, agility, forestry, wood procurement, mixed-integer programming, forest products industry, supply flexibility.

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1. Introduction

Creation of value-added products and diversification from traditional commodity focus has been sought in the forest products industry as a strategy to adapt to the new economic challenges (FPAC 2011). Significant progress has already been made in the development of bio-energy, bio-chemicals and bio-materials. However, in a highly competitive globalized market characterized by turbulence and volatility, product development is only a part of the equation; success will depend on supply chain's capability to deliver these products to markets in a timely manner (Christopher 2010). Supply chains need to be agile to capture opportunities.

Agility of forest product supply chains depends largely on the agility of wood procurement systems (WPS). WPSs are responsible for procuring wood from forests to supply raw material for all downstream manufacturing activities (D'Amours et al. 2008). The task entails delineating cutblocks, constructing roads, and conducting harvesting and transportation operations. Under the changing context, characterized by greater market volatility, WPSs are faced with an emerging challenge of fulfilling volatile demand from a diverse set of manufacturers (Hansen et al. 2013). WPSs need to be able to adjust their production accordingly whilst taking into consideration a multitude of factors (Pulkki 2003). In the past, WPSs based their production on market forecasts and placed inventory at strategic points to withstand market fluctuations (Stier 1986; LeBel and Carruth 1997). However, WPSs need to better align their production with demand in a volatile and competitive context. This entails identifying forest stands with the appropriate raw material, harvesting, and delivering it to the customers in a timely manner. Audy et al. (2012) show that WPSs are limited in their capability to change existing harvest plans to align raw materials with prevailing demand. This can be attributed to the disconnection between forest products supply chain and forest management planning as discussed in Gunn (2009).

Forest management planning is conducted using a top-down hierarchical approach aggregating and disaggregating information at the various levels to reduce complexity (Bettinger et al. 2008). Savard (2011) provides a comprehensive schematic of decisions made at each hierarchy based on a case study in Quebec, Canada. A long-term strategic plan is first devised taking into consideration ecological and social concerns to determine the annual allowable cut for a period extending over one rotation. Subsequently, the volumes calculated at the strategic level are spatially allocated at the tactical level. In the process, forest stands are aggregated to form cutblocks. A silvicultural treatment is then prescribed to each individual block allowing volume estimation by assortment. Next, an annual plan is formulated from this pool of cutblocks, attempting to match supply with demand forecast. Once the annual plan has been established, a schedule is developed for the supply chain to fulfill prevailing demand from within this annual pool of cutblocks using the silvicultural treatments already prescribed. Even if the prevailing demand differs significantly from forecast, altering silvicultural treatments to better align supply with demand is not contemplated (Gunn 2009; Savard 2011). Strictly constraining the short-term planning process in a hierarchical planning framework impedes full value-creation potential (Paradis et al. 2013).

Fixing such decisions based on a year-old market forecast can negatively impact supply chain performance. Besides market volatility, there is also the issue of accuracy concerning forest resource inventory estimation. Forest inventory data used at upper hierarchical planning levels are approximations derived through sample-based procedures; there are inaccuracies associated with estimations. Gautam et al. (2013) report that flexibility in the choice of silvicultural treatments would enable practitioners to better match supply with demand. Such flexibility could be exercised without undermining ecological and social objectives. Lussier (2009) conducted a study in the eastern Canadian context to evaluate the impact of changing prescriptions to fulfil supply chain requirements in lieu of implementing pre-determined treatments. Improvement in supply chain profits was demonstrated, whilst respecting ecological constraints. However, flexibility in silvicultural treatment was not exercised in the study, but simply flexibility in tree choice within the partial harvest treatment. Nevertheless, it provides motivation to explore the advantage of flexibility in the choice of silvicultural treatment itself at the operational level to better align supply with demand.

Prior to exercising flexibility in the choice of silvicultural treatment, the financial feasibility of the alternative treatments have to be ensured. Several studies have been conducted on the subject in recent times. Howard and Temesgen (1997) conducted a study to assess the potential financial returns from forest stands under different silvicultural prescriptions over a 30-year planning horizon in western Canada. The financial analysis included harvesting, hauling and regeneration costs. Market prices were used to calculate the revenue. The resulting net present values (NPV) indicated that a range of silvicultural treatments could be economically viable depending on stand specific parameters. Andreassen and Øyen (2002) conducted a study to estimate and compare the net present value of three silvicultural systems in central Norway: single tree selection, group selection and clearcutting. The NPV calculations were based on an assumption of perpetual application of the chosen treatment. Clearcutting consistently yielded the greatest NPV, however, other two cuttings were revealed to be reasonable options as well. Liu et al. (2007) calculated the benefit cost ratio of several different silvicultural treatments applied to forest stands in Québec. The treatments included clearcut, shelterwood and two variations of partial cuts. The result showed that clearcut generated the highest average net income, however, the benefit cost ratio was highest under partial harvest. Moore et al. (2012) conducted a similar study but with a time horizon of 200 years. Their calculation of NPV acknowledged the inherent uncertainty associated with parameters in the long-term. The median NPV values were positive for all treatments, with clearcut yielding the highest value. However, based on the simulation, there was also the possibility that clearcut could be less profitable than other treatments.

The studies discussed above demonstrate financial feasibility potential of various silvicultural treatments. However, their feasibility in the operational level wood procurement context remains to be demonstrated because the analyses were conducted from a public sector viewpoint. The following limitations were observed in regards to these studies: (i) they all assumed that infinite demand existed for all assortments produced, and could be sold at market prices to generate revenue. The assumption is unrealistic considering that mills are geographically dispersed and it is not economically viable to transport all assortments from the forest to their highest value yielding mills due to long distances; this will vary on a case basis; (ii) except in the study by Moore et al. (2012), the prices of different assortments were kept constant throughout the study horizon although an investigation of recent data reveals a high volatility in market prices. The prices have a significant impact on the revenue generated and consequently the NPV; (iii) the studies were conducted at the stand level; an analysis under a broader context is bound to vary the outcome. As an example, if a group of cutblocks were clustered in an area, economies of scale could be applied to reduce overall cost; (iv) transportation costs were excluded in their analyses except in Howard and Temesgen (1997). The exclusion of transportation cost is justifiable given uncertainty with regards to destination mills in such studies. Nevertheless, transportation cost represents a significant proportion of the overall cost, subsequently dictating feasibility of silvicultural treatments.

Thus, financial feasibility of silvicultural treatments needs to be further assessed at the operational level where data on demand and prices are more accurate. Also, at the operational level, the knowledge of the spatial setting of mills and other allocation decisions allow better estimation of harvesting and transportation costs. Numerous models have been proposed to support decision-making at the operational level. Walker and Preiss (1988) developed a mixed integer programming model to support decision-making on areas to harvest and allocation of log assortments from harvest areas to surrounding mills. Burger and Jamnick (1995) constructed a linear programming model to include decision on the harvest method to be employed. Epstein et al. (1999) incorporated bucking decisions. Karlsson et al. (2004) formulated a Mixed Integer Programming (MIP) model to incorporate harvest crew assignment in the decision-making. A MIP model that generates procurement plans taking into consideration fiber freshness is presented in Beaudoin et al. (2007). However, to the best of our knowledge, silvicultural treatment has not been explicitly included as a decision variable in operational level wood procurement model.

The objective of the study is to examine the potential improvement in supply chain performance through flexibility in silvicultural treatment decisions at the operational level. The specific goals are: (i) to provide an operational level wood procurement planning model which uses silvicultural treatment as a decision variable; (ii) to employ a mechanism to account for the impact of operational level silvicultural flexibility on long-term supply and to incorporate it in the decision-making; (iii) to quantify the improvement in supply chain profits and demand fulfillment rates. In the next section, we present the method used to realise the objectives, it includes a description of the experiment conducted and the mathematical model developed. A test case built using industry provided data is presented in section 3 to validate the proposed approach. Results from the case study and relevant discussions are presented in section 4 followed by conclusion in section 5.

2. Method

The problem was set up from the perspective of a wood procurement company responsible for harvesting cutblocks and delivering raw materials to meet demands from various manufacturing mills. It was assumed that a strategic plan, a 5-year spatial plan, and an annual plan had already been prepared based on forecast. On the market side, the prevailing demand was a random parameter that differed from the forecast. Thus the operational plan was to be redeveloped in light of the prevailing demand.

2.1 Experiment

An experiment was designed to measure the potential financial gains from allowing redevelopment of the operational level plan with alternate silvicultural treatment prescriptions. Various scenarios were constructed and simulated to quantify the benefits. The simulation process is demonstrated in Figure 1. First, a random number generator was used to simulate demands from various mills. On the supply side, there were volumes of assortments available in cutblocks that are a function of the silvicultural treatment applied. Using this information, a scenario was generated and used as input to the operational level wood procurement planning model. The first period statistics were collected from the plan generated by the model since it is the only period executed. The statistics collected included profit generated and demand fulfillment rates. Demand fulfillment rate is the percentage of the volume supplied relative to the demand. The volumes prescribed in the first period were deducted from the initial inventory and the next iteration was run with the updated demand information.

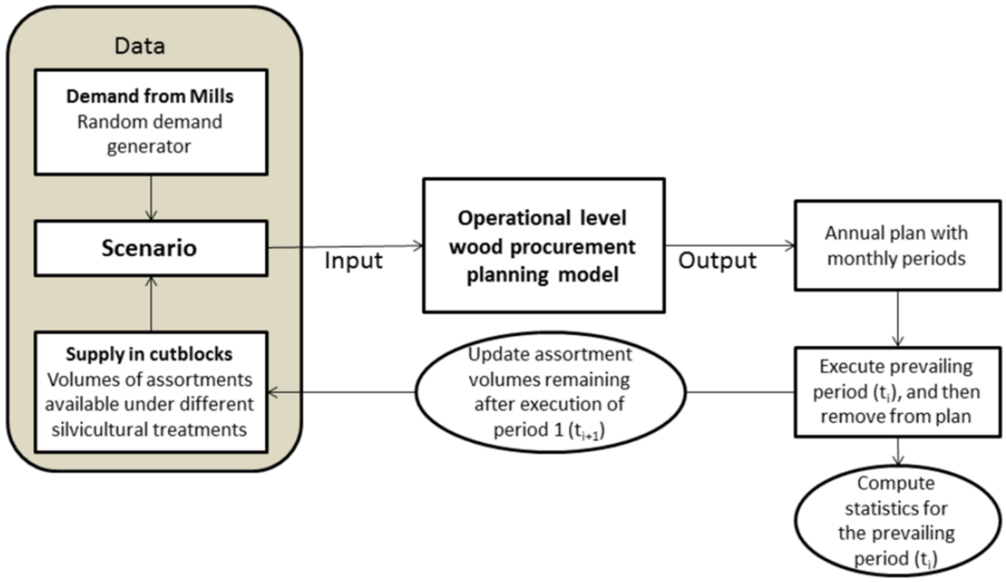

Figure 1: An illustration of the planning process simulation.

The simulated scenarios are outlined in Table 1. Scenarios 1 and 2 represent the status quo approach; there was no flexibility in the choice of silvicultural treatment. As indicated in the third column of Table 1, scenario 1 represents a setting with low demand volatility and scenario 2 represents a setting with high demand volatility. It was assumed that demand is a random parameter with a normal probability distribution. The low and high volatility represent a standard deviation that is 15% and 40% of the base demand, respectively. In scenarios 3 to 10, silvicultural treatment could be changed to improve supply-demand alignment. In scenarios 3 and 4, no additional cost was incurred to exercise this flexibility. Thus, we did not account for future impact of changing silvicultural treatment from what was initially prescribed to a cutblock. However, in scenarios 5 to 10, future impact of changing silvicultural treatment was accounted through applying different intensities of flexibility cost. The different intensities were established to conduct sensitivity analysis; further discussion on this cost is provided in section 2.2.

Table 1: The list of scenarios used for the experiment.

Scenario	Flexibility in silvicultural treatment	Demand volatility	Cost imposed based on the following silvicultural intensity		
			Extensive	Basic	Intensive
1	No	Low	Not applicable		
2		High			
3	Yes	Low	Cost not imposed		
4		High			
5	Yes	Low	√		
6		Low		√	
7		Low			√
8		High	√		
9		High		√	
10		High			√

The planning horizon for each scenario was one year divided into 12 monthly periods. The plan was executed in a receding horizon approach. The approach is depicted in Figure 2; in each prevailing period, a plan was developed for the entire horizon with knowledge of demand for the prevailing period and forecasts for the remaining periods. However, the plan was implemented only in the prevailing period. At the start of the next period, a new plan was developed using updated demand and forecast information. Both actual and forecast demands were generated randomly assuming normal distribution. The process continued until the end of the planning horizon.

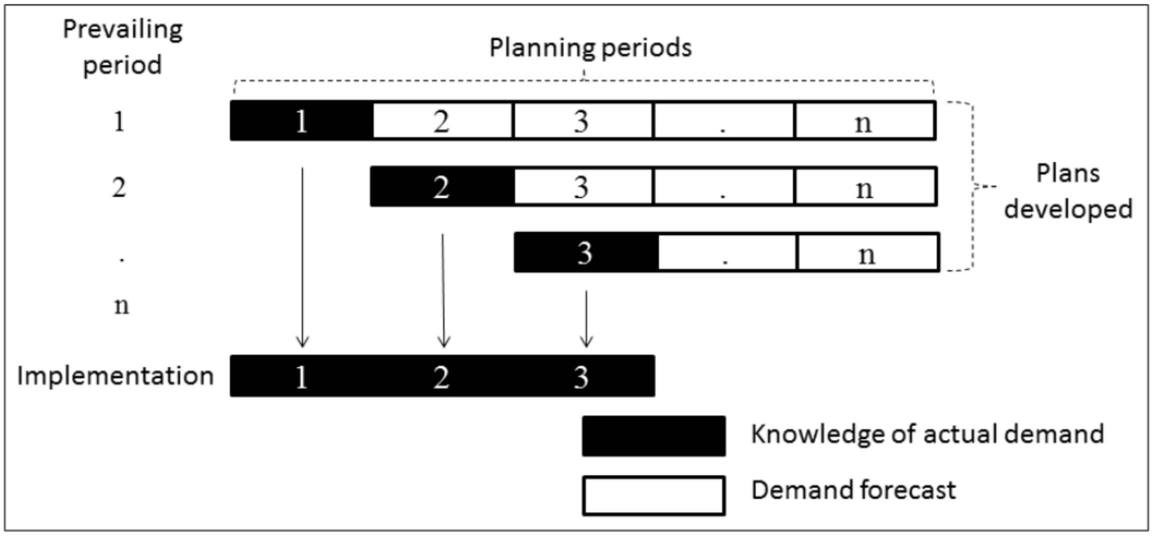

Figure 2: An illustration of the receding planning horizon approach.

2.2 Flexibility cost

The complexity in forest dynamics and forest management renders the task of anticipating the precise impact of altering silvicultural treatment at the operational level on the long-term supply quite challenging. Nevertheless, to avoid undesirable impact of operational level amendments on long-term supply, we imposed a cost in conjunction with a change in the silvicultural treatment. This is referred to as the flexibility cost. The cost was estimated based on an assumption that forest succession can be controlled through applying a silvicultural regime (Fujimori 2001; Homagain et al. 2011). A silvicultural regime is a series of interventions imposed on the cutblock over time. If the treatment was altered, we assumed that silvicultural regime could be prescribed to ensure that the cutblock still reaches an initially desired state. A sensitivity analysis was then conducted on cost associated with silvicultural regimes. The range of values used for the sensitivity analysis was based on different intensities of silvicultural regimes (Table 2). These regimes were inspired by those proposed in Bell et al. (2008) in a similar context. The costs of the three regimes were subsequently used to conduct the sensitivity analysis.

Table 2: The silvicultural regimes used to estimate flexibility cost for sensitivity analysis

Activity	Silvicultural regime		
	Extensive	Basic	Intensive
Site preparation	√	√	√
Plant		√	√
Pre-commercial thinning		√	√
Fill Plant			√
Tending			√

2.3 Mathematical formulation

The overall planning problem is illustrated in Figure 3. The objective was to maximize profit; revenue was generated through delivery of product assortments from cutblocks to customer mills and the costs stemmed from harvesting and transportation activities as well as flexibility cost. The yield of product assortments from cutblocks depended on the silvicultural treatment applied. There was also a decision to be made on harvesting systems to be employed. The cost of harvesting a cutblock depended on the productivity of the chosen system. Stand specific parameters were assumed to be uniform with regards to their influence on the productivity of harvest systems. It was assumed that the land base already had an existing road network. Only the cost associated with the portions of roads that needed to be built or upgraded to join the cutblocks to the existing network was taken into consideration and included in the harvesting cost. We assume that inventory could be stored on roadsides until demand arose in the future.

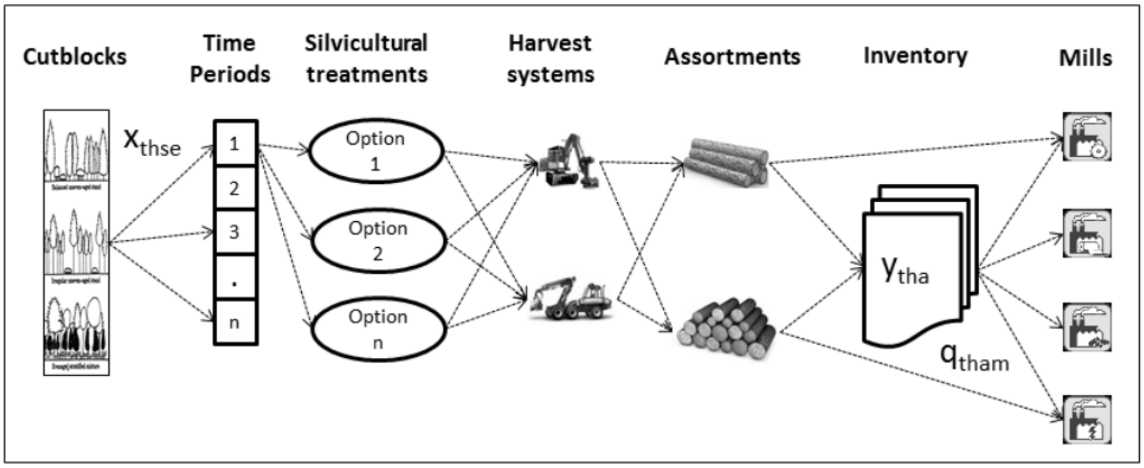

Figure 3: A depiction of the overall planning problem with the decision variables.

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 assortments *a*
M: is the set of mills *m*

Input Data

V_{hsa} maximum volume of assortment *a* available in cutblock *h* when subjected to silvicultural treatment *s* (m^3)
N_a is the selling price per cubic meter of assortment *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)
J_{hs} is the cost incurred to alter the prescribed treatment in cutblock *h* to silvicultural treatment *s* (\$)
Y^I_{ha} initial roadside inventory of assortment *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 assortment *a* demanded by mill *m* during period *t* (m^3)
V is a very small number

Decision Variables

$$b_{hse} = \begin{cases} 1, & \text{if block } h \text{ is planned for harvesting in any period using silvicultural treatment } s \text{ and harvest system } e \\ 0, & \text{otherwise} \end{cases}$$

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 assortment *a* transported from cutblock *h* to mill *m* in period *t* (m^3)
y_{tha} is the volume of assortment *a* stored in cutblock *h* at the end of period *t* (m^3)
r_h integer variable used to limit the number of periods during which cutblock h is cut

Objective Function

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

Subject to:

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

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

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

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

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

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

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

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

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

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

[12] $\sum_{s\in S}\sum_{e\in E} x_{thse} + \sum_{s\in S}\sum_{e\in E} x_{t+1,h,s,e} = r_h \quad \forall\, h$

[13] $\sum_{h\in H} r_h \leq 1 \quad \forall\; h$

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

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

The objective function (eqn. 1) was formulated as profit maximization. The first element represents the revenue generated through delivery of wood assortments to mills. The second, third and fourth element represent the variable costs associated with harvesting, transportation and inventory, respectively. The last element represents flexibility cost imposed for altering silvicultural treatment from what was initially prescribed to a cutblock.

Equations 2 and 3 are flow conservation constraints that ensure storage balance of assortments in cutblocks. Equation 2, handles the first period of the planning horizon and equation 3 handles the remaining periods. Equation 4 ensures that the volume of wood assortments transported to a mill during a particular period is less than or equal to the demanded volume. Equation 5 is a harvest capacity constraint, it ensures that the volume harvested per period is less than or equal to the maximum production capacity. Equation 6 ensures the total volume harvested in a cutblock in all periods is less than or equal to the maximum available under a silvicultural treatment. Equation 7 forces application of the same silvicultural treatment to a cutblock even if harvesting is partitioned to different periods and different harvest systems. Equations 8-9 establishes a relationship between the variables b_{hse} and x_{thse} by triggering variable B_{hse} to 1 if a cutblock is planned to be harvested over the planning horizon. Equation 10 ensures that if a cutblock is selected for harvest, the entire available volume is harvested over the planning horizon. Equation 11 ensures that the total volume delivered to all mills in each period is lower than the transportation capacity. Equation 12 and 13 limit harvesting of a cutblock to be partitioned to a maximum of two subsequent periods. Finally, equations 14 and 15 assign binary restrictions and non-negativity restrictions to respective variables.

2.4 Statistical Analysis

Friedman repeated measures analysis of variance on ranks were conducted to compare the effects of flexibility in the choice of silvicultural treatment, the different intensities of flexibility costs imposed, and demand volatility levels, on profit and demand fulfillment rates. Tukey's post hoc tests were carried out to further analyze the statistical significance effect of levels of the independent variables on the dependent variable in each model. Also, analysis of variance tests were carried out to examine effects of intensities of flexibility costs imposed on proportion of silvicultural treatments prescribed. The residuals were tested for normality and homogeneity of variance prior to conducting the tests. Any significant differences in the analysis were further analyzed using the Holm-Sidak tests.

3. Case Study

3.1 Description

A hypothetical case study was developed based on data received from a forest products company operating in Quebec, Canada. The wood procurement company operates in the boreal mixedwood forest region. The region is characterized by forests with several of the following species: black spruce (*Picea mariana* (Mill.) BSP), white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), white pine (Pinus strobus L.), red pine (Pinus resinosa Sol.), balsam fir (*Abies balsamea* (L.) Mill.), larch (*Larix larcina* (Du Roi) K. Koch), eastern red cedar(*Juniperus virginiana* L.), trembling aspen (*Populus tremuloides* Michx.), yellow birch (Betula alleghaniensis Britt.), paper birch (*Betula papyrifera* Marsh.), balsam poplar (*Populus balsamifera* L.), sugar maple (*Acer saccharum* Marshall). The company manages demand from 10 mills in the region. The acquired data contained information on demand for one horizon which was used as the base demand.

3.2 Supply

There were 50 cutblocks allocated for harvest in a one-year period with information on volumes by assortment. It was assumed that clearcut was the default treatment prescribed to all cutblocks. The volumes available under alternative treatments were therefore estimated assuming that they would be a subset of the default value. Four additional treatments were developed. Option 1 and 2 are treatments inspired by Raymond et al. (2009) where 50% of the default volume is removed from the block. They represent two variants of the extended irregular shelterwood system. Under option 1, 75% of the extracted volume is softwood while only 25% of hardwood is removed. In contrast, under option 2, 75% of the extracted volume is hardwood and 25% of it is softwood. In cutblocks with insufficient softwood or hardwood volumes, the restriction on proportion of species to be extracted was relaxed. Option 3 and 4 were treatments inspired by Ruel et al. (2007), they represent different intensities of partial harvesting of the cutblocks with 40% and 30% of the volumes being removed, respectively. The volumes under these treatments were estimated by multiplying the default values by 0.4 (option 3), and 0.3 (option 4). Data were generated for all cutblocks to specify volumes available under each option (Table 3). Log prices were obtained from the Wood producers association of Québec (SPFRQ 2013).

Table 3: Example of assortment volume table by silvicultural treatment for a given cutblock.

Assortment	Volumes available under silvicultural treatment (m³)				
	Default	Option 1	Option 2	Option 3	Option 4
Yellow birch Grade 1	16	16	16	7	5
Yellow birch Grade 2	85	85	85	34	25
Paper birch Grade 1	129	129	129	52	39
Paper birch Grade 2	1,309	1,309	1,309	523	393
Sugar maple Grade 1	0	0	0	0	0
Sugar maple Grade 2	0	0	0	0	0
Deciduous pulp	6,710	3,943	6,710	2,684	2,013
Trembling aspen 5”+	11,707	0	8,197	4,683	3,512
White pine 8”+	61	61	61	24	18
Red pine 7”+	0	0	0	0	0
Fir/spruce/pine/tamarack	23,839	16,385	5,421	9,536	7,152

3.3 Harvest and transport parameters

Two options on harvesting systems were utilized to implement the treatments: cut-to-length (CTL) and full-tree systems (FT). The productivity of the systems varies depending on the treatment being implemented. The productivity values used in the case study were estimates based on values published in Meek (2006) and Gingras (1994). The cost of transportation was estimated at $0.032·$m^{-3}$·$km^{-1}$ based on a payment rate of $80·$hr^{-1}$ and volume capacity of 50m³. Information on distances between mills and cutblocks were part of the acquired data. The hourly costs for cut-to-length and full-tree systems were estimated at Canadian (2013) $260 and $322 per scheduled machine hour, respectively, based on Gautam et al. (2010) and Puttock et al. (2005). All conversions were made using the bank of Canada inflation calculator (BOC 2013). The total harvesting cost depended on the productivity of the chosen system in a particular cutblock. With regards to flexibility cost, the costs associated with each regime were estimated using MRN (2009) and converted to 2013 Canadian dollar (BOC 2013).

4. Results and Discussion

The mathematical model was coded using the AMPL modeling language (Fourer et al. 2003) and solved using CPLEX 12.5 in a 3.07 GHz PC with 12 GB RAM. An iteration of the case study with 12 time periods contained 35,232 linear variables, 1,500 binary variables and 8,342 constraints. The optimality gap was set to within 1% and a time limit for computation was fixed at 1000 seconds. 50 repetitions of each of the 10 scenarios were run on a receding planning horizon basis for 12 monthly periods. A summary of the average profit values and demand fulfillment rates under each scenario are shown in Table 4. In general, it was found that both the profit values as well as demand fulfillment rates were higher under scenarios with flexibility in the choice of silvicultural treatment at the operational level.

Table 4: Average profit and demand fulfillment rates.

Scenario	Average profit ($)	Demand fulfillment (%)
1	20,448,971	83.6
2	19,754,999	81.6
3	21,311,902	87.3
4	20,705,123	85.2
5	21,123,213	86.7
6	21,088,338	86.8
7	20,771,571	85.8
8	20,678,285	85.8
9	20,418,854	84.6
10	20,139,077	83.5

The distributions of the profit values under the low and high volatility scenarios are shown in Figures 4 and 5, respectively. Trends under both volatility levels were similar; when given flexibility in the choice of silvicultural treatment, the profits increased and subsequently showed a decreasing trend with an increasing flexibility cost. A one-way repeated measures analysis of variance by ranks showed that there was a statistically significant difference in the profit values ($p < 0.001$). Results of the multiple comparison procedures (Tukey test) are included in the figures; boxes labeled with the same letter are not significantly different from each other. Scenarios without flexibility in the choice of silvicultural treatment (1 and 2) generated profits significantly lower than the remaining scenarios. Even with the most intensive flexibility cost imposed, the profits were still significantly higher than the scenario without flexibility in the choice of silvicultural treatment. Flexibility in the choice of silvicultural treatment permitted the model to develop a plan that procured a mix of products more reflective of the emerging demand.

Under low volatility in demand (scenario 3), an average increase in profit of $862,931 was observed when allowing flexibility in the choice of silvicultural treatment without imposing flexibility cost. The difference was reduced to $674,242, $639367 and $322,600 when extensive (scenario 5), basic (scenario 6) and intensive (scenario 7) flexibility costs were applied, respectively. Similarly, an increase of $950,124 was observed under high demand volatility (scenario 4) when flexibility in the choice of silvicultural treatment was permitted. The subsequent differences as the flexibility cost increased were $923,286 (scenario 8), $663,855 (scenario 9) and $384,078 (scenario 10). Increases in profits were greater under high demand volatility scenarios. The percentage increases were on average 5.5% (scenario 4), 5.4% (scenario 8), 4.1% (scenario 9) and 2.6% (scenario 10) under high demand volatility. The percentage increases in scenarios with low demand volatility were 2.8% (scenario 3), 2.0% (scenario 5), 1.8% (scenario 6) and 0.2% (scenario 7).

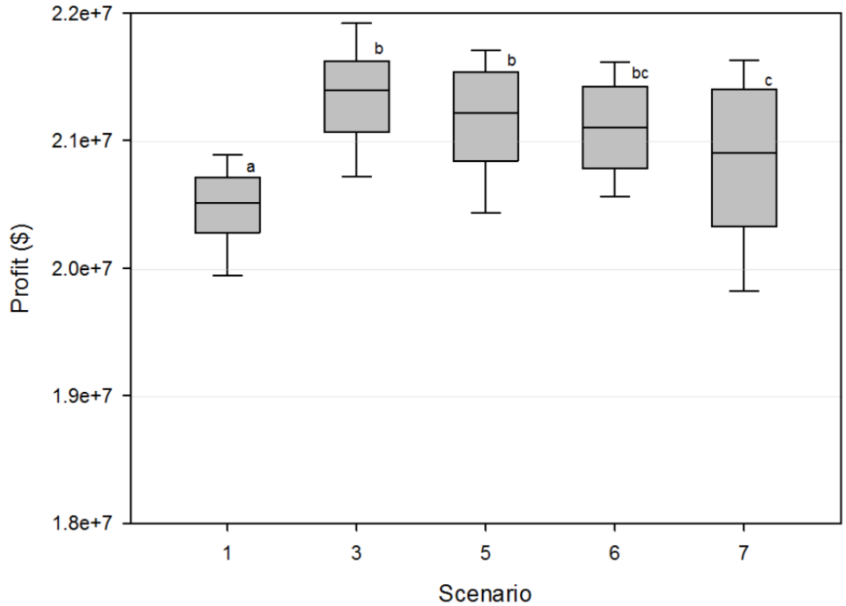

Figure 4: A box and whisker graph showing distribution of profit values from 50 experimental runs for the low volatility scenarios (scenario 1, 3, 5, 6 and 7). Please refer to Table 1 for description of the scenarios.

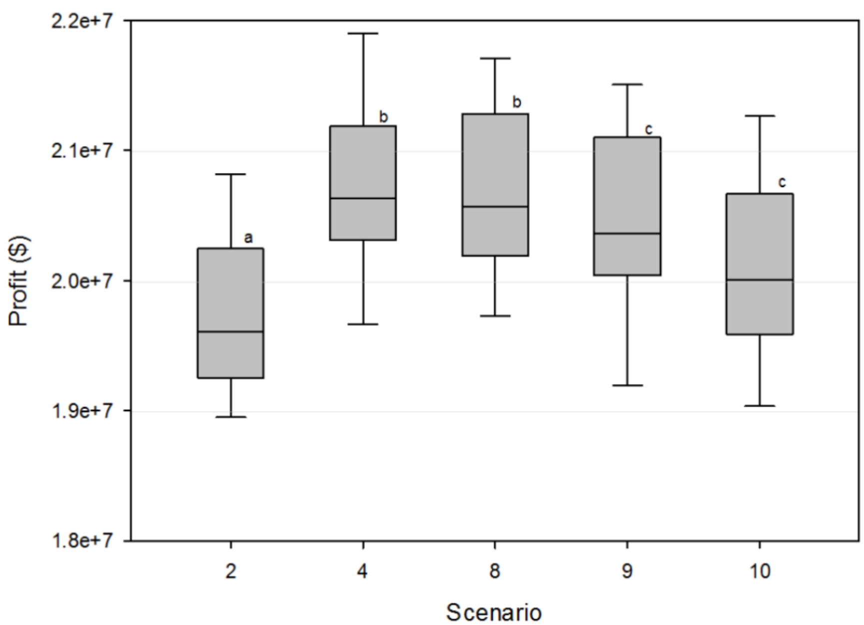

Figure 5: A box and whisker graph showing distribution of profit values from 50 experimental runs for the high volatility scenarios (2, 4, 8, 9 and 10). Please refer to Table 1 for description of the scenarios.

The distribution of demand fulfillment rates from 50 experimental runs are shown in Figures 6 and 7 for the lower and higher volatility levels, respectively. Repeated measures analyses of variance by ranks showed statistically significant difference in the demand fulfillment rates ($p < 0.001$). Results of the multiple comparison procedures (Tukey test) are included in the figures; boxes labeled with the same letter are not significantly different from each other. Flexibility in the choice of silvicultural treatment significantly increased the demand fulfillment rates. In lower volatility scenarios, the rates increased from 83.6% to 87.3% when flexibility in the choice of silvicultural treatment was permitted without imposing a cost. The rates were 86.7%, 86.8% and 85.8% when imposed flexibility costs based on extensive, basic and intensive silviculture intensity, respectively. In higher volatility scenarios, the increase in the demand fulfillments rates through permitting flexibility ranged from an average of 81.6% to 85.2%. Subsequently, imposing flexibility costs based on extensive, basic and intensive silviculture intensity led to demand fulfillments rates of 85.8%, 84.6% and 83.5%, respectively. Thus, under the status quo practice, demand fulfillment rates were lower although the assortments existed in the forest. Flexibility in the choice of silvicultural treatment would improve demand fulfillment rates, consequently, raising harvest levels closer to annual allowable cut and therefore providing increased economic benefits.

Unlike profit values, the difference in demand fulfillment rates due to providing flexibility in the choice of silvicultural treatment was not definitively greater under high volatility scenarios. Under high volatility scenarios, the increases were 3.6%, 4.2%, 3.0%

and 1.9% for no flexibility cost, extensive, basic and intensive silviculture intensity, respectively. The corresponding values for low volatility scenarios were, 3.7%, 3.1%, 3.2% and 2.2%, respectively. The greater increase in profit under higher volatility scenarios without the same increases in demand fulfillment rates can be explained through the differences in the assortment prices. The model would have focused on fulfilling demand of assortments that generated higher revenue rather than overall demand fulfillment since the objective function sought to maximize profit.

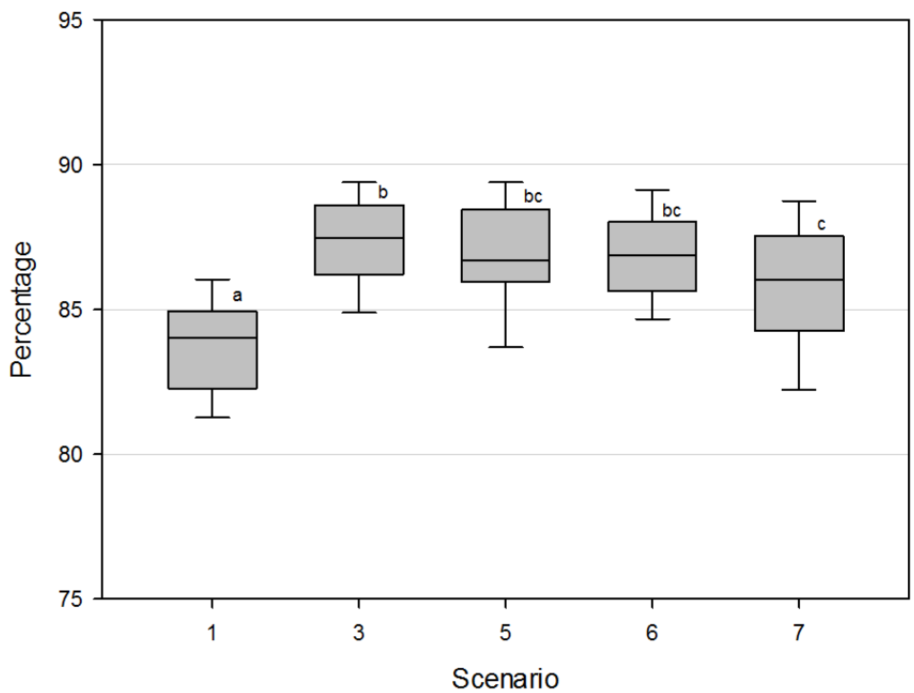

Figure 6: A box and whisker graph showing distribution of demand fulfillment rates after 50 experimental runs under low volatility scenarios. Please refer to Table 1 for description of the scenarios.

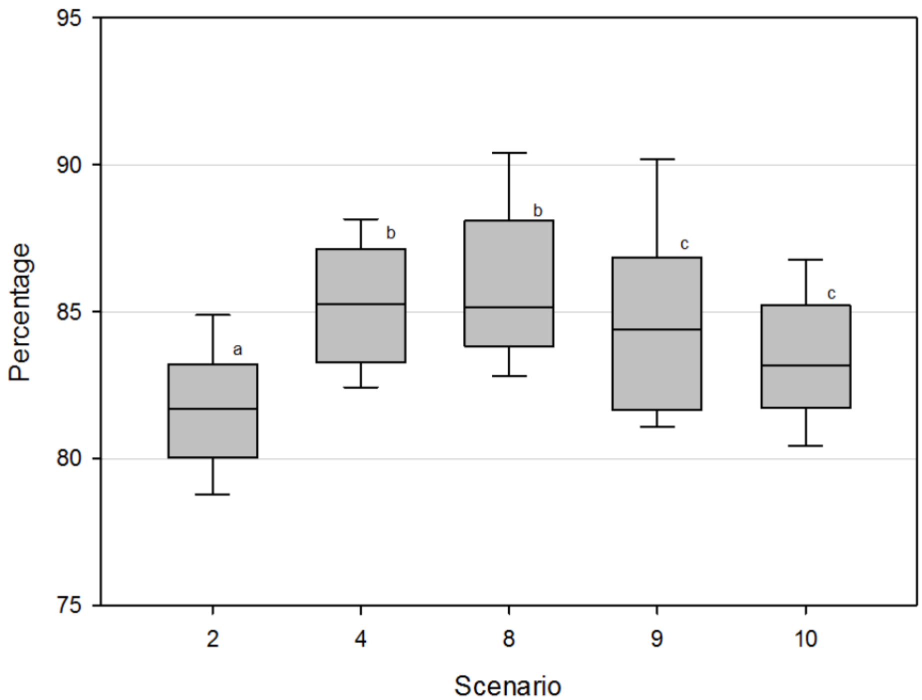

Figure 7: A box and whisker graph showing distribution of demand fulfillment rates after 50 experimental runs under high volatility scenarios. Please refer to Table 1 for description of the scenarios.

A summary of the proportions of silvicultural treatments implemented under different scenarios are shown in Table 5. The proportions reflect average values from 50 runs of the model and are based on volume. ANOVAs were carried out for each silvicultural treatment proportions prescribed under different scenarios. The results of the analyses have been included in Table 5; numbers labeled with the same letter are not significantly different from each other. The proportions of silvicultural treatments prescribed did not vary significantly with demand volatility levels. The proportions did, however, vary significantly depending on the intensity of flexibility costs imposed. Multiple comparison tests (Holm-Sidak) showed that the difference between "no cost" and "extensive" was not statistically significant but the remaining regimes all produced proportions significantly different from each other. The trend of increased application of the default treatment was observed as the flexibility cost was augmented (Figure 8).

It is interesting to note that alternative treatments were applied even in scenarios with the most expensive cost imposed. This finding suggests that all treatments with an acceptable benefit-cost ratio should be considered as an option. The prevailing demand should then dictate the decision on the treatment to be applied as the eventual profitability depends on it. With the proper decision support tool, as the one presented in this study, such shorter term adjustments are deemed feasible.

Table 5: Descriptive statistics of proportions of silvicultural treatments prescribed under different scenarios based on volume (m^3).

Basis for Penalty	Prescribed treatment	Low volatility			High volatility		
		Average	Min	Max	Average	Min	Max
No cost	Default	58.3 (5.3)[a]	46.0	70.5	58.6 (6.3)[a]	43.7	74.1
	Option 1	16.8 (4.5)[d]	7.0	27.8	15.0 (5.2)[d]	3.8	27.6
	Option 2	13.0 (5.2)[g]	2.9	25.7	12.7 (4.5)[g]	4.4	22.4
	Option 3	7.0 (2.8)[j]	0.0	12.7	8.2 (3.6)[j]	1.0	16.8
	Option 4	4.8 (2.2)[m]	0.6	10.9	5.5 (2.3)[m]	1.8	12.4
Extensive	Default	57.3 (5.5)[a]	44.5	67.8	58.2 (6.9)[a]	42.6	75.5
	Option 1	16.2 (4.5)[d]	7.8	28.3	15.0 (5.6)[d]	2.5	30.4
	Option 2	14.3 (4.2)[g]	5.3	23.5	12.3 (5.3)[g]	2.4	28.7
	Option 3	7.3 (3.4)[j]	0.5	14.9	8.9 (3.7)[j]	1.8	18.6
	Option 4	4.9 (2.6)[m]	0.2	13.2	5.5 (2.6)[m]	0.4	11.2
Basic	Default	71.6 (6.5)[b]	57.7	87.6	74.5 (5.1)[b]	63.7	85.3
	Option 1	9.9 (4.7)[e]	0.9	19.0	9.7 (4.3)[e]	0.0	18.5
	Option 2	10.0 (5.0)[h]	1.1	20.7	8.1 (3.5)[h]	1.0	17.3
	Option 3	4.8 (2.9)[k]	0.0	11.2	4.8 (2.7)[k]	0.0	10.7
	Option 4	3.6 (2.7)[n]	0.0	12.3	3.0 (2.2)[n]	0.0	9.0
Intensive	Default	81.2 (5.4)[c]	66.5	92.1	84.4 (6.6)[c]	71.4	97.4
	Option 1	6.7 (3.5)[f]	0.0	15.5	5.8 (4.7)[f]	0.0	18.6
	Option 2	6.8 (4.4)[i]	0.0	19.7	5.5 (4.0)[i]	0.0	18.2
	Option 3	2.4 (1.6)[l]	0.0	5.9	2.5 (2.2)[l]	0.0	10.4
	Option 4	2.9 (2.3)[o]	0.0	10.7	1.9 (1.9)[o]	0.0	7.0

* Values in parentheses represent the standard deviation

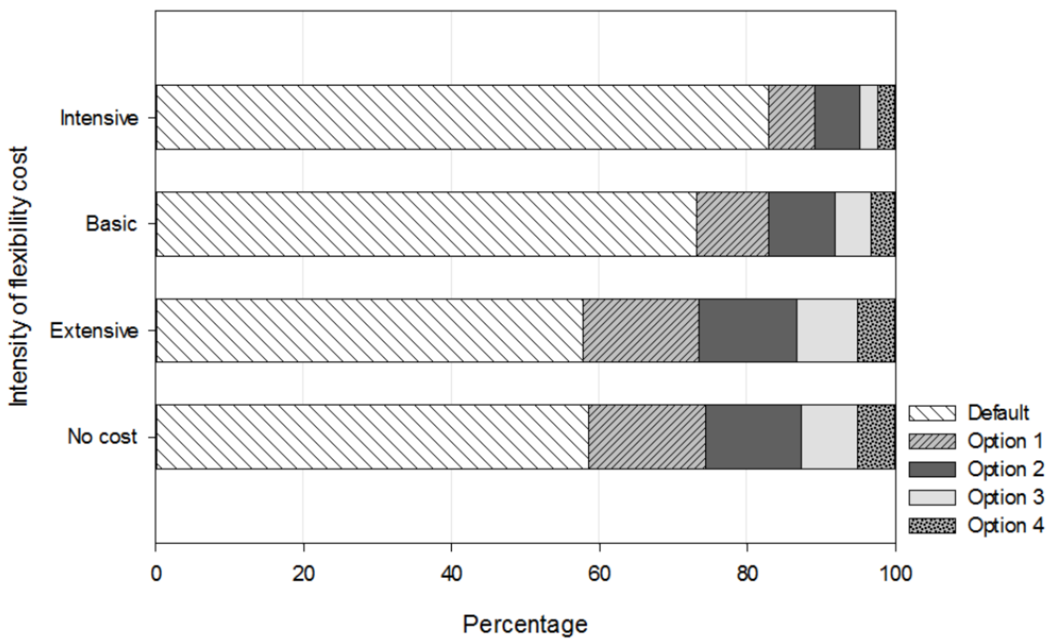

Figure 8: Proportion of silvicultural treatments prescribed under different intensities of flexibility cost imposed. High and low volatility scenarios were combined due to non-significant difference between the two.

5. Conclusion

The study was conducted to quantify the benefits of improving agility on supply chain performance and to determine the conditions under which it can be realized without impacting long-term wood supply. The proposed approach of improving agility entailed allowing flexibility in the choice of silvicultural treatments at the operational level. An operational level wood procurement planning model that includes silvicultural treatment as a decision variable was developed, and implemented to a case study. The results demonstrated that profits were significantly higher when flexibility in the choice of silvicultural treatment was allowed. This conclusion holds even when costs are imposed to account for future impacts. Profit increases were higher (in percentage) under scenarios with high demand volatility. However, the profit gains are contextual, based on the presented case study; the outcomes may differ in other settings. Nevertheless, the results provide a motivation to consider flexibility in the choice of silvicultural treatments at the operational level. Furthermore, an increase in demand fulfillment rates was also observed under scenarios with flexibility in the choice of silvicultural treatment. The absence of options on silvicultural treatment was restricting forest harvesting due to a lack of demand for the entire array of assortments produced. All things being equal, such flexibility would raise harvest levels closer to the annual allowable cut, resulting in higher benefits such as employment opportunities, as well as increased stumpage revenue.

The choice on silvicultural treatments was limited to five options in this study. In a real case, the number of options will vary depending on cutblock site parameters. The maximum potential treatments should be identified based on the site parameters, allowing managers to better align supply with changing demand. Also, future studies should focus on modeling the precise impact of altering silvicultural treatment at the operational level on long-term wood supply.

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