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EFFECTS OF DIFFERENT CUT-TO-LENGTH HARVESTING STRUCTURES ON THE ECONOMIC VALUE OF A WOOD PROCUREMENT PLANNING PROBLEM

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Abstract In this paper, we develop a Mixed Integer Linear model for a practical multi-facility wood procurement-planning problem using a cut-to-length (CTL) bucking system. This forest management problem is difficult to solve since it integrates the forest bucking problem and the multi-facility supply planning problem. A priority list approach was used to generate adequate bucking patterns for the Eastern Canadian context of operations. The model proposes a decision support with respect to: how to harvest the different cut blocks according to the bucking priority list used, and in what quantities harvested logs should be transported to saw mills. It aims at minimizing a combined non-linear harvesting cost, a transportation cost, an inventory cost and the maximization of the products value (i.e., profit maximization). The harvesting cost, used in the model, considers the non-linearity of the harvester productivity function, which is an important aspect of the decision-making process in current forest management. The model was used to compare the current bucking scenario to two new conceived ones. These scenarios allow investigating the gains and losses that could arise from the use of different bucking aggregations. More specifically, they consider the disaggregation impact on the number of different log types per block and so on its associated harvesting cost. Moreover, they aim to better understand the cost/benefit trade-off of implementing a more complex decision structure in a Canadian wood procurement context. In tests and comparisons between the scenarios,

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the results showed that the forest bucking aggregation (the actual practice) significantly reduces the forest company's profit. The results demonstrate that a simple bucking disaggregation that does not imply extra operational cost can improve the outcome.

Keywords Cut To Length harvesting system · forest bucking problem · wood procurement planning · Mixed Integer Programming

1 Introduction

Uusitalo (2005) defines the wood procurement planning as a set of technical, commercial and logistical activities. These activities are included in the process of supplying wood manufacturing mills with raw material.

In this paper, the cut-to-length bucking-based wood procurement planning problem, is presented as a combination of two classic problems: the cut-to-length bucking problem and the multi-commodity supply planning problem with multiple supply sources and demand destinations. Cut-to-length bucking is the operation of cutting tree stems into smaller logs in order to be used in further industrial process ([1], [13], [27]), using cut-to-length machinery. In this process, tree stems are cross-cut directly at the stump. It is widely used for wood procurement by forest companies since it facilitates the handling of logs and reduces soil degradation (logs are carried instead of being dragged on the ground). However, it is a divergent process that forces forest engineer to make an early transformation decision since one raw material (tree stem) produces a variety of sub-products (logs).

Improving the fit between mills' demand and the output of bucking operations has been shown as an even more important target in wood procurement development than the operational costs minimization objective [34]. In fact, a good bucking strategy has a direct impact on the end products, and therefore on the profit of sawmill. It is also an irreversible process, since it is impossible to correct a poor bucking output at any subsequent stages of transformation ([13], [33]). In addition, when the tree bucking and the wood supply planning are considered separately, some of the supply plans may be infeasible due to the heterogeneity of the forest [6].

This paper focuses on two issues. The first one is to find a near-optimal wood procurement plan, for a year of planning horizon. The main question to answer is which products to obtain from each cut block according to the bucking priority list used, and in what quantities harvested logs should be transported to sawmills. A mathematical model with a specific harvesting cost formulation is developed. The harvesting cost formulation considers the non-linearity of the harvester productivity function. Through this cost formulation, the model takes into account the impact of the number of different log types per block on the harvesting cost. This is an important aspect of the decision-making process in current forest management [1]. The model aims to increase the net profit by decreasing operational costs (harvesting, transportation and inventory costs) and optimizing the allocation of products between cut blocks.

In the second issue, the developed model was used to compare the current bucking scenario to two new conceived ones. The current bucking scenario is called the forest aggregation bucking scenario. It aims to apply the same bucking priority list per species in the whole forest. In the second, called the sector aggregation bucking scenario, the same bucking priority list is applied per species in all cut blocks of each harvesting sector (i.e., a group of cut blocks closed to each other and predefined by the forest company). In the last scenario, called the stand aggregation bucking, a bucking priority list is applied per species without any aggregation. These scenarios are defined in order to explore the effects of the harvesting aggregation structure on the total procurement cost. More specifically, they allow studying the impact of the number of the different log types on the harvesting cost, using its non-linear formulation. Thanks to a collaboration with FPInnovations, the results of the comparison are used to support Eastern Canadian forest companies. They will provide them a better understanding of the cost/benefit trade-off of implementing a more complex decision structure such as the total or partial disaggregated bucking options.

The content of this article is organized as follows. Section 2 presents an overview of the literature. Then, section 3.1 introduces the problem description, while section 4 defines the bucking priority lists and their simulation. Next, section 5 proposes the problem mathematical formulation. In section 6, a description of the three bucking scenarios is given. The data used for testing the performance of the models is introduced in section 7. After, section 8 presents the computational results. In the last section, some concluding remarks and research perspectives are proposed.

2 LITERATURE REVIEW

The wood procurement planning problem can be decomposed into the bucking optimization problem and the multi-commodity supply planning problem, presented by [6], these problems are presented in this section.

2.1 Bucking optimization problems

The bucking operation consists in cutting the fallen trees in forest cut blocks into smaller pieces (logs) in order to be used in further industrial process. Laroze (1999) classified the bucking optimization problems into three categories: the stem level, the stand level and the forest level bucking optimization problems.

2.1.1 Stem and stand level bucking optimization problems

At stem level, the objective is to find the bucking pattern that maximizes the single stem value. As cited by [13], the dynamic programming (DP) approach is generally used for stem-level bucking optimization ([28], [29], [11], [35]).

Optimal bucking for individual stems does not lead necessarily to the same result at the stand level ([17], [1], [27]). In fact, this former does not necessarily consider the diversity of trees in each stand, nor does it fulfill all the market constraints (desired volumes, qualities, length and minimum average small end diameter of logs (MSED)). The stand level bucking optimisation problem aims to maximizing the whole production value taking into account the resources availability of the stand and the customers' needs.

Marshall et al. (2006) proposed a buck-to-order planning model using different approaches to generate cutting instructions. They presented the advantages of having a buck-to-order plan in maximizing the value of the stand and in predicting the surplus volume before harvesting the stand.

In order to solve the stand level bucking optimization problem, some researchers used a two-stage model ([23], [25], [27]). In their general framework, the constrained timber procurement problem is usually modelled in the master problem and the stem bucking problem in the sub-problem. The link between the two problems and the constraints considered in each one differ from one model to another. This method is theoretically correct and computationally efficient [19]. However, the solution produced a large number of cutting instructions, which are difficult to implement by the operators of the harvesters ([19], [21], [32]).

Heuristic approaches were proposed in [12] and [20] to solve the same problem. Laroze (1997) proposed a Tabu Search (TS) heuristic based system for generating a bucking rule for each stand instead of assigning a bucking pattern to each stem class. Using a stepwise bucking algorithm, each stand bucking rule generates one distinct pattern to each class-representative stems.

2.1.2 Forest level bucking optimization problems

At forest level, the bucking problem aims to balancing stands heterogeneity and demand mix, in order to maximize the value of the forest. In fact, some forest stands are more suitable, according to their stem distribution, to produce specific product types than others. In the forest level bucking problem, this compatibility factor is considered to make the harvesting efficient and more profitable. Considering the three levels of the bucking optimization problems, the forest level is the least studied one.

As an extension of his work done in 1997, Laroze (1999) used the TS heuristic method for generating bucking rules with an LP formulation to solve the forest-level bucking optimization problem. Kivinen (2007) presented an extension of his work done in 2004. He found that adjusting the logs prices of demand matrices prior to the harvesting operation was more advantageous in stand level than in forest level bucking problems. In these works, procurements activities such as transportation of logs to different wood mills are not considered. These studies addressed only the bucking operations on homogenous forest stands (one species). They did not integrate activities involved in the process of supplying wood mills with raw materials such as transportation. They only satisfy an aggregated demand expressed in terms of product and market types (e.g., export logs, saw logs, pulp logs), and not known by wood mill locations.

2.2 The multi-commodity wood distribution problem

In the general theory, the multi-commodity distribution problem involves many decision problems ranging from short to long term planning. For a review of multi-commodity supply network planning, the reader is referred to [22]. At the strategic level (long term), decisions on locating facilities sources are considered. Allocating customers to supply points is an example of the decisions taken in the tactical planning level (mid term). For operational level (short term), transportation flows and inventory levels are addressed taken into account the customers' demand, the transportation and the stock costs. In this project, the proposed problem belongs to the operational level of planning.

Even though there are similarities between the wood procurement and the multi-commodity supply planning problems, some differences exist. First, in the forest context, there is no fixed cost for locating facilities (forest cut blocks) as it is the case in other contexts. Second, supply level in the facilities sites depends on bucking decisions. In fact, the selection of bucking patterns and the harvesting options to apply to cut blocks strongly affects the production level of different assortments. Therefore, considering the procurement decisions and the bucking decisions separately can lead to infeasible procurement plan. However, the integration of bucking decisions into a wood procurement planning problem increases its complexity [8].

Different harvesting aspects can be addressed if we deal with short term harvesting planning such as the crew scheduling [12], the control of storage in the forest and at terminals, the use of sorting yards [31] and the forwarder route planning [9]. For short term transportation planning, issues like road maintenance decisions and backhauling can be considered [5]. In some short term harvesting planning problems, bucking patterns are generally not considered because cutting instructions are provided by harvesters' on-board computers [5]. Arce et al. (2002) formulated the log product allocation problem including transport activities as a Mixed Integer Linear Programming (MIP) problem. They generated the bucking patterns for the upper level problem through simple heuristic rules. They aimed to maximizing the total net revenue at the forest level. In the problem formulation, they limited the number of different products bucked per stand but they did not consider their impact on the harvesting cost.

Epstein et al. (1999) proposed a multi-period procurement planning problem including harvesting (i.e., which stands and what volumes to harvest), bucking (what bucking pattern to use) and transportation activities (what products should be delivered to different destinations to satisfy demand). They used a column generation based approach, where the bucking patterns are included during the optimization process.

Chauhan et al. (2009b) proposed a short term supply network planning problem in which decisions on what timber assortments should be produced in pre-selected stands in order to fulfill the demand of different sawmills are taken. They used a bulk process based bucking which is a simplification of the real bucking process as they did not use inventory simulators (as in [8] and in this work) that returns the production yields resulting from the patterns used. They tested their approach on relatively small instances of the problem (number of stands < 10, number of log types < 6). Compared to the previous problems presented in the literature, they are the first to consider the impact of the number of different products in the output mix on the harvesting cost. In the problems presented above, a general approach is used. This common approach relies on a decomposition technique where bucking patterns are generated in the sub problem and included in the master problem during the optimization process. As noted by many authors ([19], [32]), this decomposition approach is theoretically correct and computationally efficient but difficult to implement due to operational constraints such as the generation of a large number of cutting instructions and the difficulty of the stand subdivision into different stem classes.

Compared to the procurement problem proposed in the literature review, the problem addressed in this paper generates a wood procurement plan, that respects the harvesting practises in Eastern Canada. It is pulled by the customers' demand and generates bucking patterns that are practical and easy to implement. To our knowledge, this paper was the first to tackle a harvesting cost function, that considers the non-linearity of the harvester productivity function. This is an important aspect of the decision-making process in current forest management[1]. The model will also help decision makers develop a more efficient forest procurement system, through the comparison between the different bucking scenarios studied.

3 PROBLEM DESCRIPTION

In this paper, the forest is divided into cut blocks that are all accessible through a road network. Their management is centralised and done by the same forest company. The annual list of cut blocks to harvest is the result of a higher level of planning problem [2]. A set of adjacent cut blocks, predefined by the forest company, constitutes a sector.

3.1 Eastern Canadian harvesting context

In this paper (see fig 1), trees are processed into final logs at the stump, using mechanized equipments (harvesters and forwarders). As reported in the literature([10]), a reduction of the harvester productivity by $1\%-4\%$ is generated by harvesting a new log type in a cut block. According to the cutting instructions, the harvester cross-cuts different product types and sorts them in different log

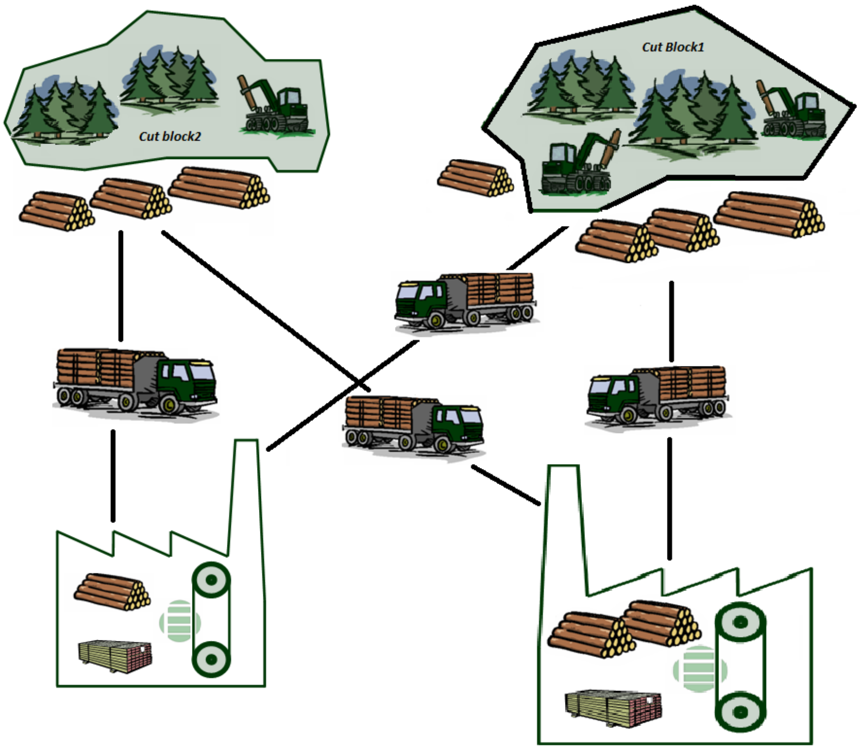

Fig. 1 Framework of the CTL-harvesting system based wood procurement planning problem

piles. This forces the boom of the harvester to move over the appropriate log pile to sort every different log type obtained. This creates a discontinuity (time lost) in the bucking operations, which decreases the productivity of the machines and increases the production cost for each new harvested log type [7]. Furthermore, an additional discontinuity is caused by cutting the same tree stem in few small logs (in terms of length) compared to cutting it in fewer long logs. Therefore, the higher the average length, the higher the productivity of the harvester.

A reduction of the forwarder productivity by $3\% - 7\%$ generated for every new log type harvested in a cut block is also reported in the literature([10]). In fact, the harvested log types are separately hauled to roadside, stored in different piles until loaded on trucks. Because different length products cannot be mixed, their hauling to roadside becomes inefficient especially when small volumes of each product type are produced. Improving machines productivity is thus a key factor for decreasing the harvest operations cost. In this paper, we consider this productivity decrease of the harvesting machinery on the harvesting cost. In its non linear formulation, the harvesting cost increases according to the number of different product-mix bucked per cut block and decreases with their average length. The harvesting cost function resulting from these considerations increases the combinatorial complexity of the classical wood procurement problem. Studying the impact of the average log length on the harvesting cost is not within the scope of this paper, even if we keep it in the FPInnovations cost equation (see Appendix).

Bucking procedure specificities. In Eastern Canada, forest cut blocks are large, heterogeneous and with high diameter variability. One consequence of these specificities, is the important number of log types that can be harvested in the same block. Consequently, generating the cutting instructions by harvesters'on-board computer cannot deliver satisfactory value recovery since it produces complex instructions for machine operators [24]. Therefore, bucking patterns are not determined by harvesters'on-board computers. In order to meet these specificities, the generated bucking patterns must be simple and easy to implement by the operators. Within this context and for practical reasons, the priority lists bucking-based method is widely used.

Actual planning approach. The actual planning approach is done manually by an experienced planner. The planner defines a bucking priority list as a combination of the demanded products for each species. This priority list is applied to all trees of same species in all cut blocks (forest aggregation bucking scenario). No optimization of the transportation cost is used. This approach has limitations with respect to the amount of time spent by the planner and with the quality of the solutions.

Transportation and inventory costs. The transportation cost, which is a significant portion of the total cost, depends on the distance between blocks and mills and the log type. A part of the transported volumes is used to meet mills demands, remaining volumes are kept in storage areas. An inventory cost is used for excess volumes.

Decision support objective. Given the annual demand of a set of geographically distributed saw mills (buck-to-order bucking) and the description of a set of forest cut blocks to harvest during the whole year, we propose a detailed mathematical model for the problem described above. The model must solve large problem instances within practical time limits. We consider the impact of the number of different log types per block on the harvesting cost, by using the specific harvesting cost formulation. Secondly, we investigate the effects of the different bucking aggregation level on the harvesting cost, using the developed model. Based on the comparison between both the conceived scenarios and the current one, we intend to help decision makers develop an efficient forest procurement system using new bucking aggregation structures. This comparison will be used to better understand the cost/benefit trade-off of implementing a more complex decision structure such as the total or partial disaggregated bucking options.

4 BUCKING PATTERN DEFINITION AND SIMULATION

In collaboration with FPInnovations, we generated a number of priority lists to use in the mathematical model.

4.1 Priority list approach

In order to take into account the Eastern Canadian bucking specifities, a bucking priority lists generation approach has been developped. In the priority list methods, logs are allocated to each stem section using a priority list ([18], [8]), instead of optimizing value over the entire stem. the position of the log-type on the priority list is important since it will control its produced volume (see figs 2). The priority list methods acheived good results in bucking optimization problems (see [19]). To match the supply with the standing timber, this method becomes suboptimal if the priorities remains unchangeable during the harvesting of a cut block. As we deal with forest level bucking optimization problem, the shortfalls of a particular cut block can be balanced by the excesses of another.

The method we propose is inspired by: the rule based bucking procedure proposed in [18], some aspects of the branch-and-bound algorithm developed in [8] and the heuristic bucking algorithm presented in [1]. In the proposed approach, a priority list corresponds to a combination of at least two of a maximum number (l_{max}) of allowable log-types obtained from a stem. Limiting the number of different product types by list has an operational impact. As said previously, the efficiency of CTL harvesters decreases as the number of log-types included in a bucking pattern increases [26]. Each product type in the priority list has an attribute, which is the minimum small end diameter (MSED).

The possible priority lists are generated considering simple heuristic rules (as in [1]). First, the order of the products defined in the priority list follows their commercial values. This choice is compatible with the forest companies' priorities. Second, products with similar value are ordered from the longest to the smallest. Third, products with the same length, are ordered according to their MSED, from the greater to the smaller. Finally, the product with the smallest length and MSED, generally a pulp log, is included as a last piece in all the generated priority lists.

As stated in [32], it is difficult to identify the class diameter of each trees. Therefore, a bucking priority list is assigned to each different species instead to each stem diameter class. These assumptions generate bucking patterns that are easy to implement by operators on the ground.

Fig2 shows an example of a priority list and its corresponding bucking patterns on trees from two different stem dimater classes. According to the priority list shown in fig2, the bucking algorithm tries to obtain as many products as possible from the first product type (A) before moving to the second type (B), and so on. Different bucking patterns (one for each tree diameter class) are obtained when applying a priority list.

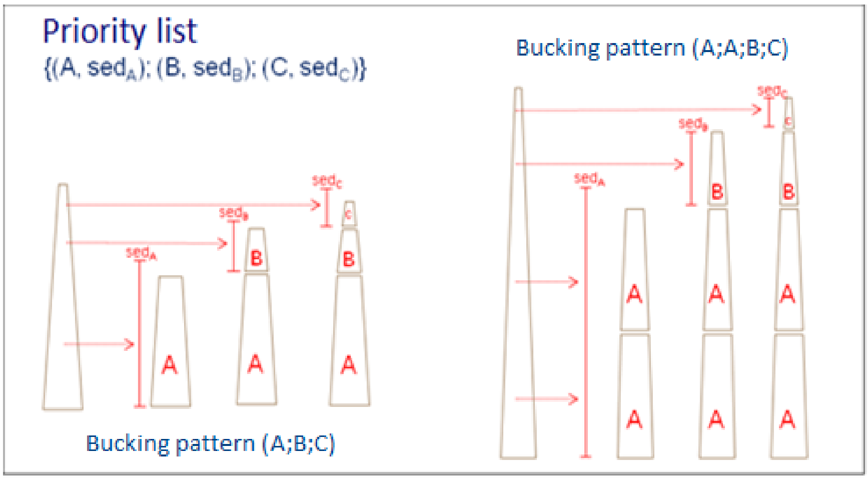

Fig. 2 Example of a priority list and its corresponding bucking patterns

4.2 Log simulator

The software FPInterface, from FPInnovations, was used to carry out bucking simulations of the generated priority list on the considered forest data set. This tool is specifically designed to simulate some activities in the forest supply chain. The harvesting module of this simulator can predict the amount of timber assortments obtained from the application of a given bucking priority list on a sample of trees from the cutting blocks. As a simplification of the real problem, we did not consider the trees' quality attributes in simulations. In practice, these simulations are done once a year before the beginning of the harvesting operations, even if the output is not be used for further applications.

5 MATHEMATICAL FORMULATION

This section proposes a formal mathematical modeling of the general problem tackled in this paper. In this mathematical formulation, the following variables and parameters are used for the three scenarios:

Parameters

B Set of forest cut blocks;

U	Set of mills;
P	Set of product types;
E	Set of species;
S	Set of sectors;
B_s	Set of blocks included in the sector s;
B_{se}	Set of blocks in the sector s and containing species e;
E_b	Set of species in block b;
B_e	Set of cut blocks containing species e;
R	Set of priority lists;
P_r	Set of different products in bucking priority list r;
d_{peu}^{Min}	Minimum demand of sawmill u for product p of species e (m^3);
d_{peu}^{Max}	Maximum demand of sawmill u for product p of species e (m^3);
p_{pe}^{u}	Sawmill u unit price for product p, species e;
V_{pe}^{br}	Volume of the product p available when bucking the species e of block b, according to the priority list r (output of the simulation);
C_{bupe}^{T}	Unit transportation cost between block b and mill u for product p of species e ($\$/m^3$);
C_{upe}^{S}	Stock cost of product p, species e in mill u ($\$/m^3$);
PE_p^e	Penalty used when harvesting small volume of product p, species e;
BIF_b^{re}	Bucking incentive factor on using a bucking priority list r on a species e of block b;
Ptg	Percentage of the total volume harvested in a given block b;
M	Large number, for example equal to the value of the largest cut block's standing timber;

Variables

x_{pe}^{bu}	Flow of product type p, species e from block b to mill u (m^3);
y_{rn}^{be}	Binary variable: takes value 1 if bucking priority list r is applied to species e of block b when n different products are obtained from b; 0 otherwise;
z_n^b	Binary variable: takes value 1 if n different products are obtained from block b; 0 otherwise;
k_{pe}^{br}	Binary variable: takes value 1 if the volume of product p, species e, in block b, obtained when bucking e using priority list r is under a certain pourcentage of the total harvested volume in b; 0 otherwise;
t_{pe}^{br}	Binary variable used for modelling purpose: takes value 1 if bucking priority list r is not applied to block b; 0 otherwise;
s_{pe}^{bu}	Stock of product p, species e from block b in mill u (m^3);

5.1 Harvesting Cost Calculation

The unit harvesting cost considers the non-linearity of the harvester productivity function. More specially, it considers the number of different log types harvested per block, which is a delicate aspect of the forest management decision process. In mathematical modelisation, it leads to the use of binary variables in Mixed Integer Linear Programming (MIP) formulations. In this problem formulation, we use a harvesting cost function defined by FPInnovations. This cost function is composed of three factors. The first factor addresses the correction on the number of different assortments in each block. In the second, a correction on the average length of logs obtained in a cut block is included. The average length is calculated using the resulting volumes generated from harvesting all the cut blocks and the length of the products obtained. The third one is the road side cost (C_b^H). It is specific to each cut block and expressed in ($\$/m^3$). We used mathematical modelling and approximation techniques in order to adapt this cost function and keep it linear.

5.1.1 FPInnovations harvesting cost function

The first factor used in the model is $f(n)$, where n is the number of different products obtained from block b. We introduced index n to variables y_{rn}^{be} to linearise it. The unit real harvesting cost C_{bn}^{RH} for cut block b, if n different products are obtained from it, is determined using the following equation:

$$C_{bn}^{RH} = f(n)\left[g(y_{rn}^{be})\right]C_b^H \tag{A}$$

where

f, g Empirical non linear functions determined by FPInnovations (see Appendix for calculation details);

5.1.2 Approximated harvesting cost

In order to linearize the objective function, we also approximate the second correction factor. Because we apply a bucking priority list per species, we can safely approximate the average length of the logs in the whole cut block weighted by its total volume by the sum of the different average length of logs per species weighted by their respective total volume (see Appendix for computation details). The average length of logs per species weighted by their total volume, when using a priority list r is $h(V_{pe}^{br})$. We will test this approximation in section 8.1. The unit approximated harvesting cost C_{bern}^H is pre-calculated for each priority list r, applied to each species e in a given cut block b, if n

different products are obtained from it, as follow:

$$C^H_{bern} = f(n)\left[h(V^{br}_{pe})\right]C^H_b \tag{B}$$

5.2 Mathematical Model

Assuming that the unit harvesting cost for each block is pre-calculated as in Equation (B), a mixed integer linearized mathematical formulation of the problem's common part to the three scenarios (P_1) is shown below:

Model

$$\begin{aligned}
(P_1)\quad \text{Max} &\sum_{b\in B}\sum_{e\in E_b}\sum_{p\in P}\sum_{u\in U} p^u_{pe}x^{bu}_{pe} - \sum_{b\in B}\sum_{e\in E_b}\sum_{r\in R}\sum_{p\in P_r}\sum_{n\in N} C^H_{bren}V^{br}_{pe}y^{be}_{rn} \\
&- \sum_{b\in B}\sum_{e\in E_b}\sum_{p\in P}\sum_{u\in U} C^T_{bupe}(x^{bu}_{pe} + s^{bu}_{pe}) - \sum_{b\in B}\sum_{e\in E_b}\sum_{r\in R}\sum_{p\in P_r}\sum_{n\in N} PE^p_e V^{br}_{pe}k^{br}_{pe} \\
&- \sum_{b\in B}\sum_{e\in E_b}\sum_{r\in R}\sum_{p\in P_r}\sum_{n\in N} BIF^{re}_b y^{be}_{rn} - \sum_{b\in B}\sum_{e\in E_b}\sum_{p\in P}\sum_{u\in U} C^S_{upe}s^{bu}_{pe}
\end{aligned}$$

subject to

$$\sum_{n\in N} z^b_n = 1 \quad \forall b \in B \tag{1}$$

$$\sum_{e\in E_b}\sum_{r\in R} y^{be}_{rn} = nz^b_n \quad \forall b \in B \text{ and } \forall n \in N \tag{2}$$

$$\sum_{n\in N}\sum_{r\in R} y^{be}_{rn} = 1 \quad \forall b \in B \text{ and } \forall e \in E_b \tag{3}$$

$$\sum_{u\in U}(x^{bu}_{pe} + s^{bu}_{pe}) = \sum_{r\in R}\sum_{n\in N} V^{br}_{pe}y^{be}_{rn} \quad \forall b \in B, \forall e \in E_b, \forall p \in P \tag{4}$$

$$d^{Lw}_{peu} \le \sum_{b\in B} x^{bu}_{pe} \le d^{Up}_{peu} \quad \forall u \in U, \forall e \in E_b, \forall p \in P \tag{5}$$

$$PtgV^b - V^{br}_{pe}\sum_{n\in N} y^{be}_{rn} \ge M(k^{br}_{pe} - 1) \quad \forall b \in B, \forall e \in E_b, \forall r \in R, \forall p \in P \tag{6}$$

$$PtgV^b - V^{br}_{pe}\sum_{n\in N} y^{be}_{rn} \le M(k^{br}_{pe} + t^{br}_{pe}) \quad \forall b \in B, \forall e \in E_b, \forall r \in R, \forall p \in P \tag{7}$$

$$t^{br}_{pe} \le 1 - \sum_{n\in N} y^{be}_{rn} \quad \forall b \in B, \forall e \in E_b, \forall r \in R, \forall p \in P \tag{8}$$

$$k^{br}_{pe} \le \sum_{n\in N} y^{be}_{rn} \quad \forall b \in B, \forall e \in E_b, \forall r \in R, \forall p \in P \tag{9}$$

$$y^{be}_{rn}, k^{br}_{pe}, t^{br}_{pe} \in \{0, 1\} \quad \forall b \in B, \forall r \in R, \forall e \in E_b, \forall p \in P, \forall n \in N \tag{10}$$

$$x^{bu}_{pe}, s^{bu}_{pe} \ge 0 \quad \forall b \in B, \forall e \in E_b, \forall p \in P, \forall u \in U \tag{11}$$

The problem's objective function consists in maximizing the global profit. In this objective, the first term presents the net revenue of the total harvested products (the timber pricing system is based on fixed product-specific log prices ($\$/m^3$) given by mills without quality consideration). The second term gives the sum of respectively: the harvesting cost, the transportation cost, the penalty (PE_e^p) and the bucking incentive factor (BIF_b^{re}) that is described below as well as the stock cost.

Constraints (1) and (2) are defined to count the number of different log types harvested in each cut block. Constraint (3) means that we use only one bucking pattern per species per block to harvest. Constraint (4) states that the flow of product p, species e, out of block b must respect the total supply of that product available in the block. Constraint (5) means that the flow of product p, species e, out of all the cut blocks and into mill u must be between the lower d_{peu}^{Min} and the upper d_{peu}^{Max} bounds of the demand. Constraint (10) states that the variables are binaries. Constraint (11) is a non-negativity constraint.

In practice, it is not desirable to harvest a volume of a specific product that is under a certain percentage (Ptg) of the total volume harvested in a given block b ($V^b = \sum_{n\in N}\sum_{e\in E_b}\sum_{r\in R}\sum_{p\in P_r} V_{pe}^{br} y_{rn}^{be}$). In fact, harvesting small amounts of a product type leads to transporting small amounts of wood from cut blocks sometimes located far away from wood mills which is not economic. A penality term (PE_e^p) is used in order to balance the proportions of the harvested volume of each product type in each block. Constraints (6) to (9) are added to the model in order to formulate this aspect. This increases the complexity of the model, since the number of binary variables increases.

Furthermore, a good harvesting planning model at the forest level must consider the composition and the characteristics of the cut block in order to cut only logs that are compatible with it. Therefore, if the majority of trees in a giving cut block are large and long, it is more convenient to produce thick and long logs from them. Consequently, it is advantageous to apply a priority list that contains such logs. BIF_b^{re} enables this by prioritizing bucking priority lists that are more suitable to the internal composition of each block to harvest (see Appendix for calculation details).

6 CASE STUDIES

In this paper, we study three different bucking scenarios. In these scenarios, we explore the effects of different bucking aggregation levels on the harvesting cost. In fact, applying the same bucking priority list to different tree species is not appropriate since they are not similar in geometry and structure. Similarly, each forest cut block represents a unique composition of trees in terms of species, number and diameter. Again, forest sectors have different areas, density and species mixture. Consequently, applying the same species specific bucking priority list to a set of cut blocks may lead to a sub-optimal use of the wood resources. Although, it simplifies the general management of the harvesting operations. We wish to understand the cost/benefit trade-off of implementing a more complex decision structure in the wood procurement planning than the one used in this context.

In this section, we present a description of each of the harvesting scenarios. In the examples given in figs 3, 4 and 5, we assume that we have a forest composed of 2 sectors (actually not limited by borders as it is in the figures). Each of the sectors includes 2 cut blocks, and each cut block contains 2 species E_1 and E_2 (the blocks may contain up to 5 species in this paper).

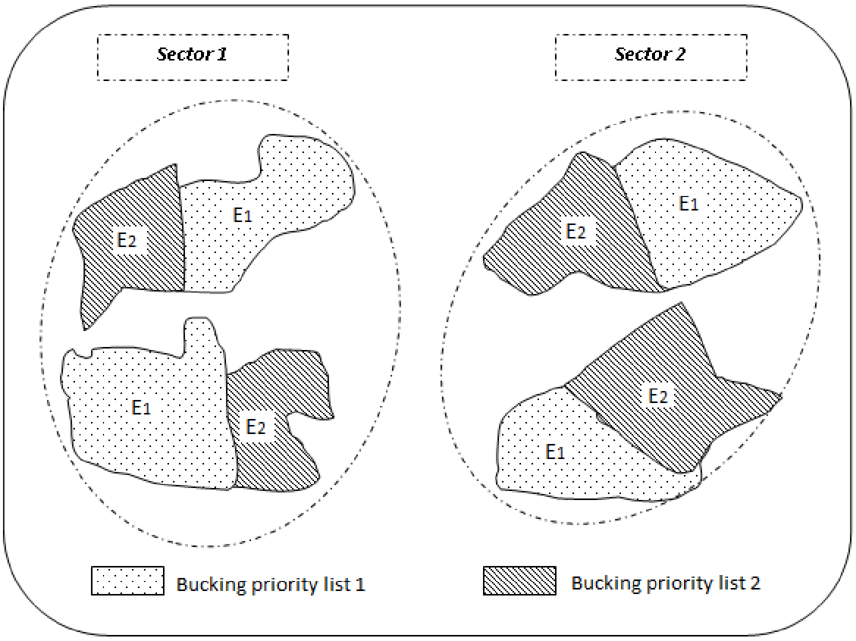

Fig. 3 Forest-level aggregation bucking scenario (scenario 1)

6.1 Scenario 1: Forest-level aggregation bucking scenario

This scenario reflects the current bucking planning procedure but differs by the optimization of the allocation of logs to mills. It is be considered for comparison as the base scenario. In this scenario, we apply the same priority list per species in all the cut blocks of the whole forest (complete aggregation). Therefore, the requested products per species must be included in the priority list used, in order to satisfy the mills'demand. According to FPInnovations, this scenario is adopted in practise since it is the most simple way of managing harvesting operations. In fig 3, a first priority list is applied to species E_1 (the hatched region) and a second (the dotted region) to species E_2, in the whole forest.

To model this scenario, we added constraint(13) to the common linearized formulation $(P1)$. This constraint states that if a bucking priority list is applied to a givin species it must be applied to all similar species in all the sectors and their corresponding blocks.

$$\sum_{b' \in B} \sum_{n \in N} y_{rn}^{b'e} = |B_e| \sum_{n \in N} y_{rn}^{be} \quad \forall b \in B, \forall e \in E_b, \forall r \in R \tag{13}$$

6.2 Scenario 2: Sector-level aggregation bucking scenario

In this case of partial aggregation, we consider only a priority list to the same species in all the cut blocks of each sector. Compared to the first scenario, the current one gives more flexibility for choosing the priority list without constraining the management of the bucking operations or changing the harvesting equipments.

In fig 4, we can observe that the bucking lists assigned to species E_1 (respectively species E_2) in Sector1 and sector 2 are different.

We added constraint(14) to the linearized model $(P1)$ to formulate this sce-

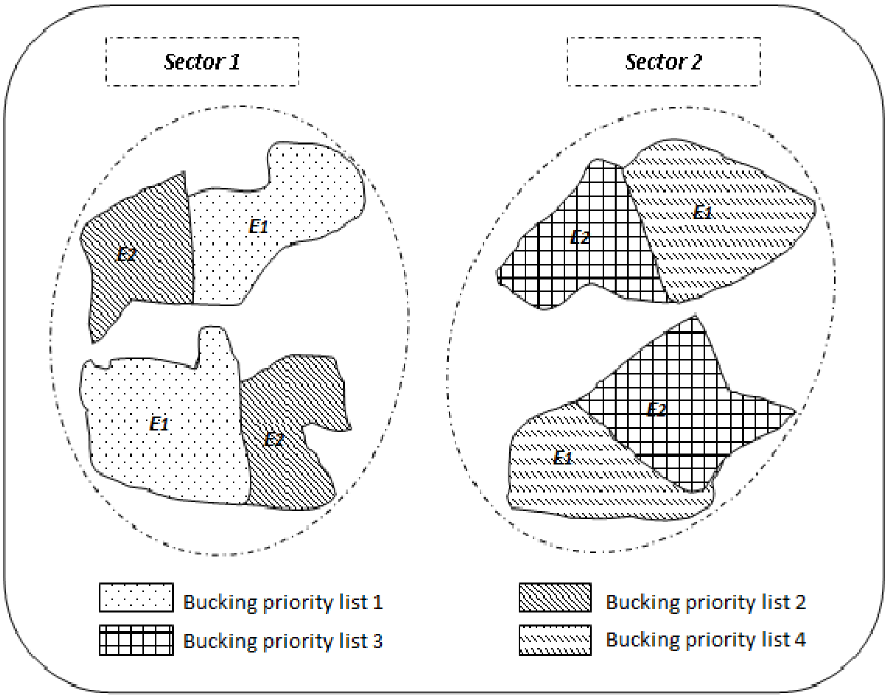

Fig. 4 Sector-level aggregation bucking scenario (scenario 2)

nario. This constraint insures that if a species in a given block and sector is bucked by a priority list, this list must be assigned to all the similar species in the remaining blocks of the sector.

$$\sum_{b' \in B} \sum_{n \in N} y_{rn}^{b'e} = |B_{es}| \sum_{n \in N} y_{rn}^{be} \quad \forall b \in B, \forall e \in E_b, \forall r \in R \tag{14}$$

6.3 Scenario 3: Stand-level aggregation bucking scenario

In scenario 3, we did not add any aggregation to the definition of the bucking procedure. It is presented in the mathematical formulation given in $(P1)$. Different priority lists per species can be applied in different blocks and sectors. An illustration of this bucking scenario is shown in fig 5. In this figure, different bucking lists are assigned to species without restrictions.

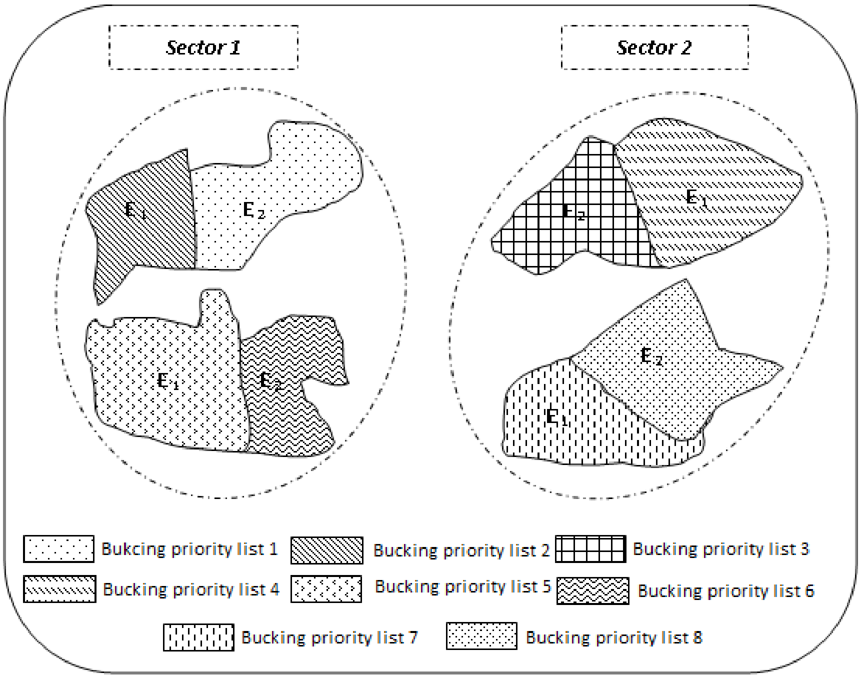

Fig. 5 Stand-level aggregation bucking scenario (scenario 3)

7 DESCRIPTION OF DATA

The data used for testing and evaluating each of the three scenarios consisted of 30 heterogeneous and mature cut blocks in Eastern Canada, occupying 3673 ha and harvested during approximately one year. Each block contains at least two of these five species: white birch (WB), black spruce (BS), poplar (POP), jack pine (JP) and balsam fir (BF). The annually harvested volume is about 580 000 m^3. In table (3), we present respectively the: sector, its corresponding blocks, the area in hectar (ha) of each block, the volume par ha (m^3/h)of each species.

Table 3 Cut blocks inventories used in the problem

Sect	Blc	Area (ha)	VH_WB (m^3/ha)	VH_BS (m^3/ha)	VH_POP (m^3/ha)	VH_JP (m^3/ha)	VH_BF (m^3/ha)
0	0	190	0,00	54,86	17,46	112,03	0,00
1	1	107	0,30	37,71	43,80	135,70	0,90
2	2	4	1,17	57,16	12,26	42,67	2,04
	3	15	1,17	57,16	12,26	42,67	2,04
	4	159	1,17	57,16	12,26	42,67	2,04
	5	187	1,17	57,16	12,26	42,67	2,04
3	6	11	0,00	57,16	0,00	63,71	0,00
	7	102	0,00	57,16	0,00	63,71	0,00
	8	5	0,00	57,16	0,00	63,71	0,00
4	9	17	0,94	55,10	62,34	78,68	2,16
	10	101	0,94	55,10	62,34	78,68	2,16
5	11	5	0,94	55,10	62,34	78,68	2,16
	12	113	0,94	55,10	62,34	78,68	2,16
6	13	23	0,94	55,10	62,34	78,68	2,16
	14	56	0,94	55,107	62,34	78,68	2,16
	15	15	0,94	55,10	62,34	78,68	2,16
	16	38	0,94	55,10	62,34	78,68	2,16
	17	125	0,94	55,10	62,34	78,68	2,16
7	18	261	1,73	65,76	22,81	57,64	2,97
	19	603	1,73	65,76	22,81	57,64	2,97
8	20	148	8,12	52,64	6,61	11,37	25,29
	21	218	8,12	52,64	6,61	11,37	25,29
9	22	476	1,16	42,39	35,58	118,22	1,01
	23	106	1,00	68,44	15,51	38,42	0,06
10	24	59	0,00	65,09	2,57	27,83	0,02
	25	60	0,00	65,09	2,57	27,83	0,02
11	26	74	0,66	62,77	74,10	54,05	5,60
	27	174	0,66	62,77	74,10	54,05	5,60
12	28	77	0,17	59,01	0,00	0,04	2,54
13	29	144	0,28	77,75	37,20	70,81	0,28

In each demand instance, there were a potential of 25 log-types (five log length multiplied by five species). These product types vary in terms of species, length and MSED. The log specifications for each product are given in table 4.

To test the performance of the developed models, 10 instances of demand forecast were used. The total demanded volume was nearly constant, but the demand for individual product types vary greatly. The average demanded volume is about 8% under the standing timber in all the blocks, which is an acceptable proportion of waste in the current harvesting practises. Also, it

Table 4 Products specifications in the problem

ProductID	Log length (cm)	MSED (cm)
1	502	17
2	440	15
3	380	12
4	320	10
5	257	7

represents about 2.5% of the average total volumes obtained when harvesting all the blocks by each of the priority lists.

8 COMPUTATIONAL EXPERIMENTS AND DISCUSSION

In order to accomplish the computational tests, the MIP models were solved using the commercial LP package CPLEX v12.1 via its C++ concert platform. The problems were set up with 16 priority lists.

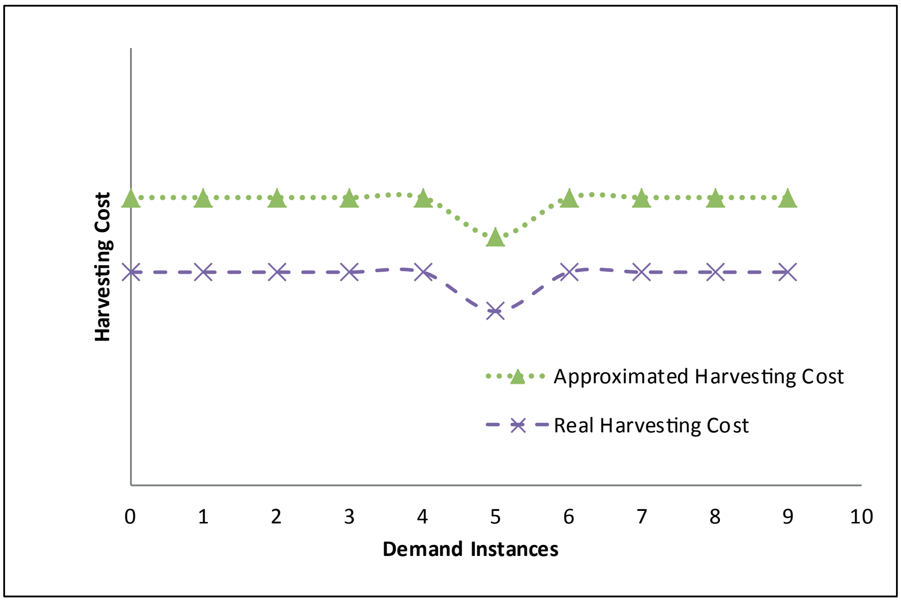

Fig. 6 Comparisons between the real and the approximated harvesting cost of scenario 1

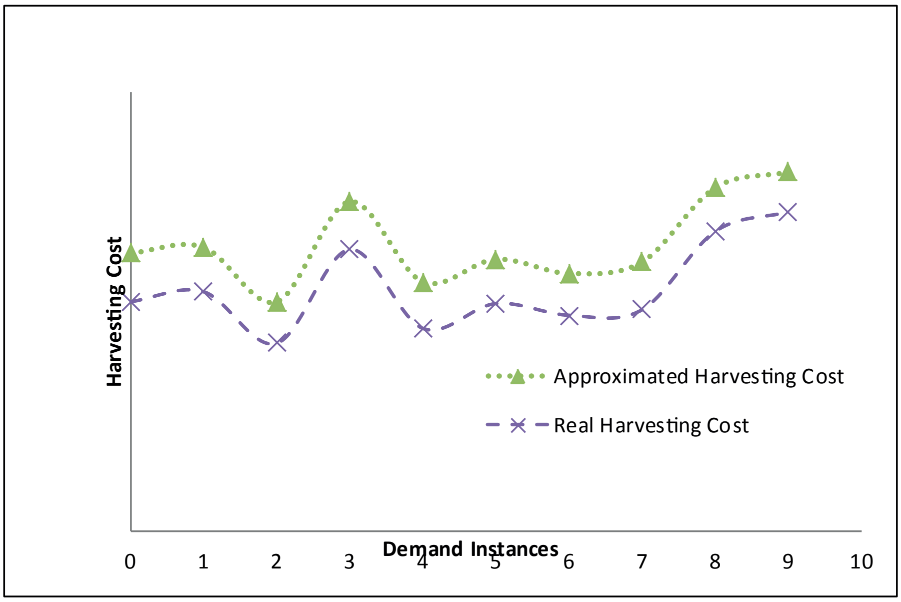

Fig. 7 Comparisons between the real and the approximated harvesting cost of scenario 2

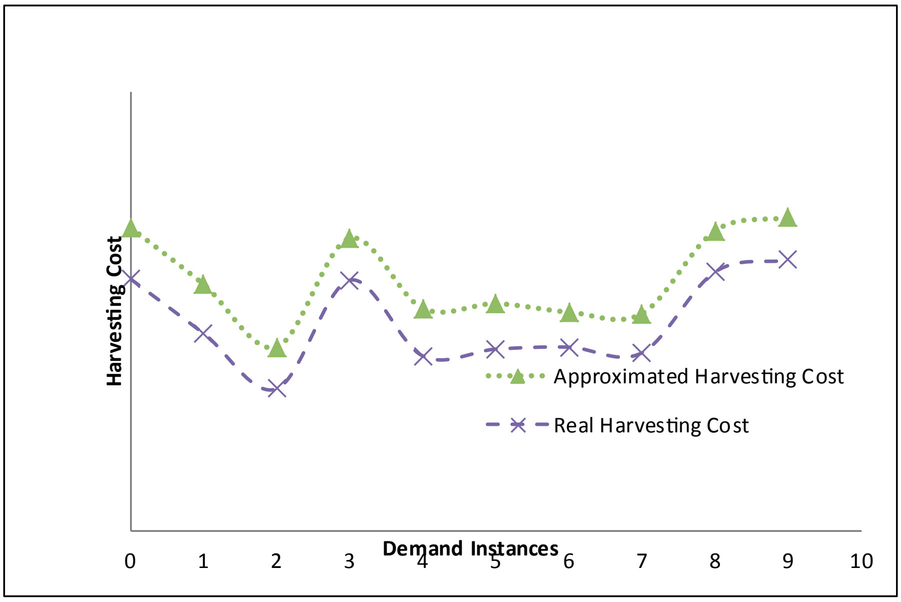

Fig. 8 Comparisons between the real and the approximated harvesting cost of scenario 3

8.1 Real harvesting cost calculation

As previously stated in section 5.1, the problem addressed in this paper has a complex objective function that is non linear and cannot be tackled by commercial softwares. Therefore, an approximated harvested cost has been used instead of the real harvesting cost. This approximation is validated by FPInnovations since the impact of the average length on the harvesting cost is still maintained if we use the approximation when applying a bucking pattern per species. In fact, products from different species and having the same length cannot be mixed on the ground. Therefore, calculating the average length by species is allowable. We calculate the real harvesting cost for each scenario, using the variables values obtained by the model solution. we observed that the approximated and the real harvesting costs have the same behaviour (figs 6, 7 and 8). The real harvesting cost value is always slightly under the approximated one for all the tests. The difference between their values (respectively between the values of the approximated and the real profit) is under 0.007$. In the next section, all the comparisons between the scenarios are done using the real harvesting cost and its corresponding profit.

8.2 Results and discussions

The model contains 28259 constraints and 94711 variables where 87180 are binaries. Six hours was the maximum allowable solution time. In fact, previous tests demonstrated that the average solution gap after 6 hours for all the tests is under 5%. (Avg) represents the average of the different values in each column in the tables.

Table 5 presents the different demand instances (Ins), the CPU time in seconds (Time) and the average of the numbers of different product types per cut bloc (N_{moy}) for the first scenario solved to optimality. Then, the average of the numbers of different product types per cut block (N_{moy}) and the solution gap in percentage (Gap) for scenario 2 (respectively for scenario 3).

Table 6 shows for each demand instance (Ins), the increase (%) of the global profit (Profit), the revenue (Revenue) and the total supplied volume to different customers (Supply), in the sector aggregation scenario (respectively in the stand aggregation scenario) compared to the forest aggregation one (the base scenario).

Table 7 gives the decrease (%) in the sector aggregation scenario (respectively of the stand aggregation scenario) with respect to the base one, of the operational costs (the harvesting C_R, the stock C_S and the transportation costs C_T), in the penalty PE on harvesting small amount of products' volumes, and in the bucking incentive factor BIF on using a bucking priority list r on a given block b.

8.2.1 Discussions

All the experiments we have carried out showed that the model we proposed find a good solution within reasonable time limits (see table 5). The optimal solution for the current bucking scenario (the base scenario) was obtained in less than 85 seconds. A near optimal solutions (average gap $< 0.5\%$) for scenarios 2 and 3 were found within 6 hours. Their solution time is significantly longer comparing to the base scenario, since the bucking alternatives considered in the MIP model are larger.

Table 5 Comparisons between forest, sector and stand aggregation scenarios

	Forest aggregation scenario		**Sector aggregation scenario**		**Stand aggregation scenario**	
Ins	Time	N_{moy}	Gap	N_{moy}	Gap	N_{moy}
1	82,42	22,26	0,63	15,3	0,42	13,97
2	69,25	22,26	0,43	15,6	0,31	15,23
3	55,95	22,26	0,39	15,13	0,26	14,53
4	82,24	22,26	0,63	15,16	0,2	14,7
5	84,08	22,26	0,49	15,06	0,25	14,96
6	76,14	21,8	0,46	15,46	0,19	14,63
7	61,16	22,26	0,34	15,16	0,24	14,76
8	60,92	22,26	0,58	14,83	0,32	14,53
9	60,58	22,26	0,37	15,23	0,15	14,86
10	61,57	22,26	0,26	14,6	0,14	14,6
Avg	**69,43**	**22,21**	**0,46**	**15,15**	**0,25**	**14,68**

Both conceived scenarios provide potential profit improvement compared to the current bucking scenario. This result does not depend on the demand instances. Results shown in the table 6 indicate an increase of the profit between 5% and 11% in the sector aggregation bucking scenario with respect to the base scenario. We observe a similar situation when considering the stand aggregation bucking (a potential profit increase of 5 to 12% compared to the base one). To analyse deeply the causes of this improvement, we report in tables 6 and 7, four factors having the largest impact on the profit compared to others.

The first factor is the increase (between 5% and 11%) in revenue. This increase is due to larger volumes supplied to customers (table 6). Scenarios 2 and 3 give more flexibility to the problem to choose a bucking plan, that generates an output close to the upper limit of the mills' demand. A better use of standing timber to satisfy the demand of different products ($3,89\%$ increase in supplied volume) minimizes also the surplus volume. The better demand fulfilment implies a decreae of the inventory cost, which is the second influencing factor.

In the third factor, we report an average decrease of ($3,6\%$) in the harvesting cost. This is mainly due to the decrease of the number of the different

Table 6 Percentage increase in sector and stand aggregation scenarios compared to the current one

	Sector aggregation scenario			**Stand aggregation scenario**		
Ins	Profit	Revenue	Supply	Profit	Revenue	Supply
0	10,62	4,86	5,23	10,81	5,04	5,42
1	8,99	3,88	4,20	9,28	3,98	4,31
2	5,60	1,92	2,06	5,93	2,00	2,15
3	11,42	5,69	5,96	11,91	5,87	6,13
4	8,52	3,63	3,93	8,91	3,74	4,03
5	8,45	3,61	3,89	8,87	3,78	4,05
6	7,55	2,98	3,12	7,81	3,07	3,20
7	8,23	3,39	3,75	8,67	3,62	3,97
8	6,71	3,18	3,19	7,08	3,34	3,35
9	5,12	2,13	2,12	5,37	2,26	2,25
Avg	**8,12**	**3,53**	**3,74**	**8,46**	**3,67**	**3,89**

product types harvested per cut block. A result that we confirmed when calculating N_{moy} (it is about 22 in the base scenario and decreased to about 15 in scenarios 1 and 2) in table 5. This result is consistent with the mathematical formulation of the harvesting cost giving in Equation (A). It showed that the disaggregation we proposed reduced the number of different log types per block which leads to a harvesting cost decrease.

The fourth factor we analyze is the penalty (PE). It decreased (an average decrease of $22,27\%$) since we harvest less small quantities of products. This practical aspect has an influence on the value loss caused by manipulating small amount of volumes. In scenarios 1 and 2, there is no obligation to apply the same bucking priority list per species to all the cut blocks. The generated bucking plan tends to limit the number of different products per block, considering the non linear havesting cost. Therefore, the limited number of products chosen per cut block are harvested in larger volumes.

Table 7 Percentage decrease in sector and stand aggregation scenarios compared to the current one

	Sector aggregation scenario					**Stand aggregation scenario**				
Ins	C_R	C_S	C_T	PE	BIF	C_R	C_S	C_T	PE	BIF
0	3,77	66,81	*0,01	17,31	1,88	3,52	62,42	*0,50	19,95	2,55
1	3,66	51,91	0,18	21,09	1,95	4,11	54,16	0,25	27,71	1,08
2	4,21	36,79	0,72	15,01	1,19	4,70	40,06	0,91	16,38	0,68
3	3,21	72,04	*0,31	26,38	*0,18	3,54	76,33	*0,18	24,52	0,08
4	4,05	54,49	0,74	17,25	0,56	4,35	57,21	0,84	28,13	0,43
5	3,52	55,08	0,68	18,77	2,31	4,01	58,91	0,82	25,22	1,40
6	3,91	47,90	0,90	16,32	2,47	4,25	49,35	0,96	18,91	1,86
7	3,85	51,23	0,09	30,88	1,83	4,31	53,56	0,05	29,30	0,83
8	3,01	42,98	*0,09	17,09	*0,78	3,45	45,33	*0,05	18,24	*1,49
9	2,81	28,88	0,14	15,21	1,66	3,32	31,34	0,17	14,30	0,56
Avg	**3,60**	**50,81**	**0,31**	**19,53**	**1,29**	**3,96**	**52,87**	**0,33**	**22,27**	**0,80**

* : Percentage increase

In both sector and stand aggregation scenarios, the incentive factor BIF decreased slightly. In fact, in these scenarios, there is an ample flexibility for the models to choose between different priority lists that are more suitable to the characteristics of the cut blocks and able to satisfy the total demand in the same time. However, it does not affect very much the profit since the model favours demand satisfaction, which is consistent with the nature of the factor and the mathematical formulation given in P_1.

Moreover, the profit increment is not affected by the changes in the transportation cost. In fact, almost the same volume of logs is transported in each scenarios. The transported volumes are either supplied to mills or stocked. In the first scenario, the largest volumes of extra volumes are registered. The procurement plan corresponding to scenario 1 allocated these volumes to the nearest mills to the cut blocks, thus decreasing the transportation cost (by decreasing the distance between the blocks and the mills since there is no specific demand destinations for extra volumes).

Comparison between the sector and stand aggregation scenarios.

When comparing the sector and the stand aggregation scenarios, we report a slight improvement in the profit of the second one (stand aggregation). This improvement is the result of the minor decrease in inventory cost, harvesting cost and the increase of supplied volume and revenue. This situation probably occurred because the aggregation degree of cut blocks in different sectors is not important. In fact, only one sector contains 5 cut blocks (respectively 4 and 3 cut blocks) and all the remaining sectors contain two or one blocks. And usually the sector contains only one large cut block (large area) with smaller one (table 3). Therefore, the impact of stand aggregation scenario will be less visible in this situation since the wood procurement plans (generated solution of both scenarios) are very similar.

9 CONCLUSION

The models addressed in this paper proposes a multi-facility wood procurement plan for a cut-to-length (CTL) bucking system. A priority list approach was used to generate adequate bucking patterns for the Eastern Canadian context of operations. The proposed procurement plan maximizes the profit while coordinating several activities involved in the wood supply chain. A linearized integer programming formulation describing the complexity of the global problem is presented.

The developped model provided a good solution for a practical size problem, within a reasonable time limit. The model was used to compare two new conceived bucking scenarios to the current one in use. This study has shown that both conceived scenarios generated larger profit (between 5% and 11%

more) than the forest aggregation one (the base scenario). Value loss occurs in various steps along the forest to mill value chain such as: the harvesting cost, the inventory management and the order fulfillment level. Scenarios 2 and 3 induce a decrease in the number of different products per blocks, which generates a potential harvesting cost decrease ($> 3\%$) .

To conclude, we believe that some strategic changes in the harvesting structure,*without a major shift in the technology in use*, in form of disaggreagation presented in scenarios 2 and 3 would be very profitable for the forest companies. However, we recognize that the use of the priority list bucking approach is effective for the relatively simple, but real, market restrictions considered in this project. As a future research direction, an extended version of the problem to treat a multi-period wood procurement plan for a cut-to-length (CTL) bucking system using sort yards can be considered.

Appendix

Here we present the detailed formulation of the harvesting cost and the proposed approximation. We will also give the details on some parameter used in the mathematical model.

A Detailed harvesting cost calculation

A.1 The real harvesting cost

For notation simplicity, we introduce index n similar to ($P1$). The unit real harvesting cost C_{bn}^{RH} per cut block, if n different products are obtained from it, is determined using the following equation:

$$C_{bn}^{URH} = n^{\gamma}\left[\beta\Big(\Big(\sum_{e\in E_b}\sum_{r\in R}\sum_{p\in P_r} l_p V_{pe}^{br} y_{rn}^{be}\Big) \Big/ \Big(\sum_{e\in E_b}\sum_{r\in R}\sum_{p\in P_r} V_{pe}^{br} y_{rn}^{be}\Big)\Big)^{\alpha}\right] C_b^H \quad (1A)$$

where

$\beta > 1$, $(\gamma, \alpha) < 1$	Empirical constants determined by FPInnovations;
l_p	Length of product type p;

Therefore, the real harvesting cost per cut block is calculated using Equation (2A).

$$C_b^{RH} = \sum_{n\in N} C_{bn}^{URH}\Big(\sum_{e\in E_b}\sum_{r\in R}\sum_{p\in P_r} V_{pe}^{br} y_{rn}^{be}\Big) \quad (2A)$$

A.2 The approximated harvesting cost calculation

The unit approximated harvesting cost C_{bern}^{UAH} is pre-calculated for each priority list r, applied to each species e in a given cut block b, if n different products are obtained from it, as follow:

$$C_{bern}^{UAH} = n^{\gamma}\left[\beta\Big(\Big(\sum_{p\in P_r} V_{pe}^{br} l_p\Big)/\Big(\sum_{p\in P_r} V_{pe}^{br}\Big)\Big)^{\alpha}\right] C_b^H \tag{1B}$$

Therefore, the approximated harvesting cost per cut block follows:

$$C_b^{AH} = \sum_{n\in N}\sum_{e\in E_b}\sum_{r\in R}\sum_{p\in P_r} C_{bern}^{UAH} V_{pe}^{br} y_{rn}^{be} \tag{2B}$$

B Calculation details of the bucking incentive factor

The penalty factor BIF_b^{re} is calculated for each species e in a block b, bucked using priority list r as follow:

$$BIF_b^{re} = \sum_{c\in C_e}\left[\Big(\sum_{p\in r}\theta(1 - l_p/L_c)\Big)/|r|\right] V_c^{be} \tag{C}$$

where

C_e Set of tree diameter classes of species e;
L_c Average length of trees diameter class c;
l_p Length of product type p;
$|r|$ Number of different products in the priority list r;
θ Empirical positive constant;
V_c^{be} Volume of tree diameter class c, of species e, in cut block b;

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