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Locating Satellite Yards in Forestry Operations

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Abstract. This study concerns the location of satellite yards in the Thunder Bay region (Ontario, Canada). The problem was modeled as a Capacitated Facility Location Problem which was solved using a mixed integer linear programming model with CPLEX. The primary objective was to help the Bowater management team determine how satellite yards could be employed in the chip supply process used by the private sub-contractors working for them. Different scenarios related to a variety of important problem parameters were studied and analyzed in order to assess their repercussions on the solution. The results obtained identify the most appropriate sites for the satellite yards, as well as permitting interesting conclusions about the different scenarios studied to be drawn.

Keywords. Forestry, location, satellite yards.

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1. Introduction

This study concerns the location of satellite yards at the Bowater complex at Thunder Bay, Ontario, Canada.[1] A leading producer of coated and specialty papers and newsprint for many years, Bowater Incorporated began its Canadian manufacturing operations at Corner Brook (Newfoundland, Canada) in 1938. Their corporate headquarters are situated in Greenville, South Carolina (USA). The company employs nearly 7000 people. Bowater owns a total of 12 pulp and paper mills in Canada, the USA and South Korea. In addition to these pulp and paper mills, the company also operates one converting facility and 10 sawmills, one of which is located in Thunder Bay. Bowater's operations are supplied from the approximately 308 800 acres of private timberland owned or leased in North America, and the nearly 11.3 million acres of public timberlands in Canada. In addition, the company is one of the world's largest consumers of recycled newspapers and magazines, owning and operating six recycling plants.

Prior to its acquisition by Bowater in 1998, the Bowater complex in Thunder Bay was owned by Avenor Inc., a company from Quebec. This complex, located on the Kaministiquia River, houses one of the largest pulp and paper mills in Canada, including two kraft paper mills, one thermo-mechanical pulp mill for newsprint, a recycling plant, a biomass boiler and a cogeneration plant.

Each year, Bowater's Thunder Bay complex receives and transforms nearly four million cubic meters of wood chips and wood pulp to produce newsprint and kraft pulp. Bowater targets mainly black spruce and jack pine for softwood pulp, and birch, aspen and poplar for hardwood pulp. Its total annual production capacity is approximately 489 000 metric tons of bleached softwood kraft pulp and 490 000 metric tons of newsprint. Primary materials are supplied to the Thunder Bay mills by three principal types of suppliers, each with their own cutting blocks. Buchanan Lumber Sales, Inc. is the first supplier. This Ontario company, whose business is conducted only in this province, is an essential component of Bowater's operations, supplying 30% of Bowater's wood chip requirements. The second type of supplier is the sub-contractors, the multiple independent companies that furnish all or part of the wood chip demand. These independent companies also supply more than 30% of the pulp mills' requirements. Bowater also call upon private sub-

[1] All information provided on this company is available in the following references: Bowater (2006), Favreau et al. (2005) and Nonki (2005).

contractors when they run out of one or more varieties of wood, or when the stocked quantities of certain woods are low or completely exhausted.

1.1. Problem presentation

Faced with the expansion of national and international sales, the multiplication of products with shorter and shorter life cycles, and clients' constantly more specific needs, Bowater, in order to differentiate itself from its competitors, decided to adopt the just-in-time supply management system used worldwide. This decision was motivated by the company's desire to keep its stock of wood chips as low as possible in an effort to reduce storage costs, while producing only the quantities really asked for by its clients. Thus, for the last several years, all of the Thunder Bay pulp mills have been managing their supplies according to this just-in-time principle. In addition, Bowater established a policy requiring the quantity of primary materials in stock to always be less than the quantity needed for two weeks of production.

However, the current supply procedures are not well adapted to just-in-time management policies. Consequently, the company's mills now risk running out of stock, with the gravity of the risk depending on the period of the year. Certainly, since the Bowater Thunder Bay mills are primarily supplied through in-woods chipping (i.e., the subcontractors fell the trees and then chip the wood themselves before transporting the chips to the mills), extracting the wood from the forest is difficult during rainy periods and the spring thaw, given the low weight-bearing capacity of the terrain. In addition, during these periods, vehicle maintenance and logging road upkeep cost more than during the rest of the year. As a result, the problems related to primary materials supply in a just-in-time system generally keep the mills operating at half capacity, provoking high monetary losses for the Thunder Bay complex. In fact, Bowater estimates that operating costs for the Thunder Bay complex would be $100 000[2] per day to produce nothing, and the site would cost over a million dollars to close.

One viable solution that would improve the supply situation at Bowater in general, and at the Thunder Bay pulp and paper mills complex in particular, would be to set up satellite yards. Appropriate use of such facilities could reduce the length of the primary materials supply cycle, and thus the risks of stock shortages, with their attendant consequences. Clearly, chipping operations

[2] All monetary figures are given in Canadian dollars unless otherwise specified.

could be carried out, entirely or in part, using the facilities in these satellite yards. The private sub-contractors would then only have to transport the different varieties of log, set the wood down at the satellite yards, and proceed with chipping operations when Bowater asks for more wood chips. Of course, if it proved less profitable for a certain cutting sector to use the satellite yards, in-woods chipping could remain the method of choice for that sector.

Figure 1 shows the location of the Bowater Thunder Bay complex and the 23 cutting sectors in their respective forest zones, as well as the network of paved public roads and logging roads, the latter of which are generally private, belonging to a contractor in the area. The cutting sectors regroup hundreds or even thousands of the cutting blocks in the forest estate, destined for the mills in Thunder Bay. Setting up satellite yards at the intersection of one or more public roads and one or more logging roads appears to make economic sense. Since the logging roads belong to the contractors, the weight limitations for trailer trucks on public roads in Ontario are not in force, making economies of scale possible: increasing the mass load transported, while reducing the number of trips made between the cutting sectors and the satellite yard.

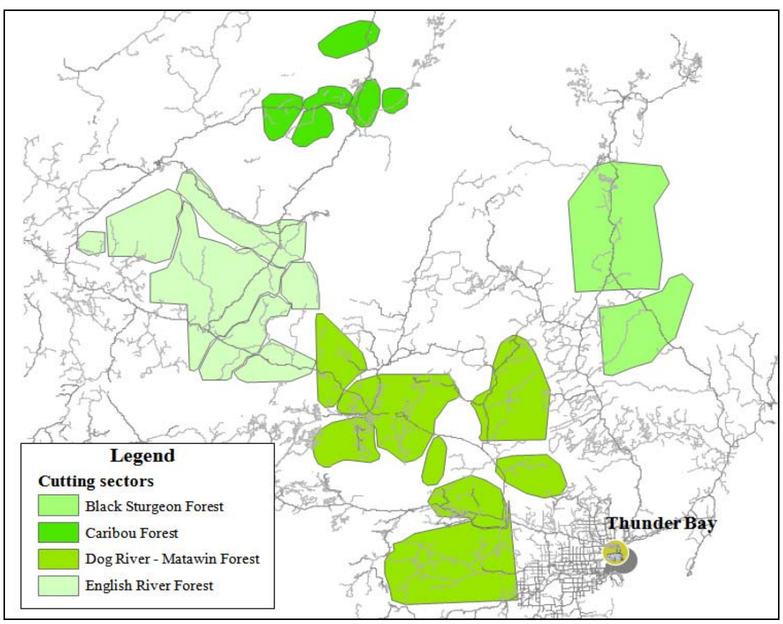

Figure 1: Map showing the Bowater Thunder Bay complex and the cutting sectors, as well as the public/private road network.

In light of the previous remarks, answers to the following questions must be found:

- How many satellite yards should be set up?

- Where should these satellite yards be located?
- Should each cutting sector be assigned to a satellite yard?
- If so, which satellite yard should be chosen?

To find these answers, a Capacitated Facility Location Problem (CFLP) can be solved. A schematized version of this problem is given in Figure 2.

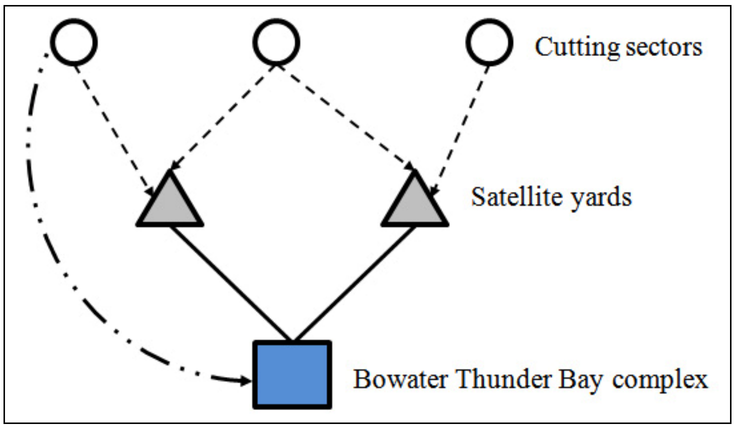

Figure 2: Graphical representation of the Capacitated Facility Location Problem.

1.2. The recommended solution approach

In order to solve the satellite yard location problem, we modeled Bowater's situation in Thunder Bay as a general mixed-integer linear programming problem. We then solved it, first on a small scale, taking only ten potential sites into account, and then on a larger scale, taking 127 potential sites into consideration. The objective of our model is to select the best locations for the satellite yards, while minimizing the total costs of supplying wood chips to the pulp mills via private sub-contractors.

1.3. The organization of this article

Section 2 contains a review of the literature about Facility Location Problems (FLP), primarily with capacity constraints. This section is divided in two parts: one dealing with general models and one with models in the field of forestry. Section 3 describes the problem in detail, and Section 4 formulates the mathematical model. Section 5 presents both the data used in this model and in our solution process. Section 6 provides the results obtained, including those from a sensitivity analysis of the model, and compares these results with the current situation and with results reported in a previous study by FPInnovations – FERIC Division (Forest Engineering Research Institute of Canada). Section 7 offers our conclusions.

2. Literature review

The first mathematical formulation of the CFLP was proposed by Davis and Ray (1969). These authors consider a set I of destinations, a set J of potential sites, and a capacity q_j for each of the potential sites. The objective function of their model is to minimize the total transportation costs and the costs of setting up a facility on the selected sites. Their constraints ensure that every demand for a destination i is completely satisfied and require a facility be set up at a site j if any demand has to be fulfilled there.

More recently, Wu et al. (2006) developed a solution method that takes general setup costs into account. These costs are divided into two groups: the general setup costs that are generated when a facility is set up on a given site, and the connection costs generated when a destination is assigned to a facility. They assume that several facilities can be set up at a single site, which generates different setup costs for the diverse facilities, depending on the site at which they are situated. It is also possible that the facilities at a single site share common expenses, for example, administrative costs. Unlike the previously mentioned authors, Wu et al. also take into account a set *K* of product types.

Klincewicz (1990) has studied a related problem which consists in locating consolidation terminals between the different sources and destinations in the network and then to decide, for each source-destination pair, if the transportation should be direct or if it should pass through one of the consolidation terminals. When a product is sent towards a consolidation terminal, it provokes additional costs due to product storage during transit. Klincewicz also considers the economies of scale that occur when the size or the volume transported increases, implying a decrease in the per unit transportation costs.

In the context of forestry operations, Paredes and Sessions (1988) developed a three-step solution method for a CFLP for satellite yards. Their objective is to determine the number of yards necessary, as well as their location. They solve the problem using mixed-integer linear programming. Lin et al. (1996) have proposed an analytical model combining mixed linear programming and a financial analysis method for a CFLP targeting an oriented strandboard production plant. In addition to solving the problem using mixed linear programming, they also analyze the discounted cash flow in an effort to insure the economic advisability of the investment in terms of the selected site and size of the production plant. Finally, a strategic planning study conducted by Troncoso and Garrido (2005) groups three main problems—a production problem, a facilities location problem, and a freight distribution problem—all connected to the forestry domain. Their model is designed to solve the three problems simultaneously, with the objective of minimizing the present value of the total costs.

3. Operational methods at Bowater's Thunder Bay pulp and paper mills

To facilitate understanding of our mathematical model, in this section, we will first describe the main features of Bowater's operations, notably those related to the supply of primary materials for their mills. Then, we explain how in-woods chipping operations are conducted and how a satellite yard operates.

3.1. Supply

Bowater's Thunder Bay pulp and paper mills have adopted a primary materials supply management system based on the just-in-time concept (Nonki 2005). This system allows the company to base their production on the quantity really required instead of relying on economies of scale. Still, their main objectives remain unchanged: diminish production costs, reduce financial needs, and remain competitive on the international and national markets. With this just-in-time approach, Bowater is endeavoring to maintain less than a two-week supply of primary materials in stock at its Thunder Bay mills. However, this new supply management system does not appear to work as well for Bowater as it has for other companies using just-in-time practices. In fact, the Thunder Bay mills now run a high risk of running out of primary materials. For example, Bowater has assessed the risk of running out of wood chips as extremely high with only one week's worth of materials stored in the mill's warehouses.

The magnitude of this risk varies with the period of the year. For example, the spring thaw has important repercussions for most forest product companies. During this period, more restrictive vehicle weight regulations are enforced on Ontario's public road network (Ontario Ministry of Transportation 2007). Given the wide variety of temperatures, the humidity, and the ground freeze/thaw cycles, the roads are considerably more fragile during this time period than throughout the rest of the year. These weight restrictions mean that Bowater sub-contractors either need to use a larger fleet of trailer trucks or make more trips with the same number of trucks in order to maintain a constant supply of wood chips for the pulp and paper mills. This necessity entails a significant increase in operational costs.

The spring thaw has an even greater impact on the logging roads, and thus on harvesting operations. Depending on the characteristics and the properties of the materials constituting these roads (e.g., solidity, road slope, rugosity, load-bearing capacity), the damage can be considerable. During the spring thaw, the snow melts, and the logging roads thaw quite rapidly. The resulting water is quickly absorbed by the upper layers of soil. Rapidly saturated with water, these layers turn to mud, transforming the roads into softened structures with a diminished load-bearing capacity. The foundations of certain roads become so deteriorated that they are, for all intents and purposes, impracticable. Combined with the weight and the repeated movements of the harvesting machines over the same terrain, this deterioration leads to ruts and cracks in the roads, a situation that does not improve until the materials lying just under the upper layers of the soil are completely thawed and dried out.

A greater quantity of harvesting machines is also required during this period of the year. Because the machines' mobility is highly reduced, the operating time needed to produce the same volume of chips is longer than under normal conditions. Combined with the need to tow broken down machines out of the forest due to the impracticability of the roads, this reduced mobility affects the productivity of the contractors and rapidly increases operating costs, notably in terms of operator salaries, fuel, and machine maintenance costs. In addition, the Ontario government continues to apply new laws and regulations in an effort to protect the zones in which ground vegetation and minerals have been damaged by the repeated movements of these harvesting machines. The end result is that contractors can well expect their harvesting activities to be curtailed even more.

Thus, all contractors are nearly obliged to interrupt their harvesting operations during the spring thaw. The roads become so muddy that it is practically impossible to go and retrieve the wood from the cutting blocks. As a result, both the quantity of wood chips delivered to pulp and paper mills and the mills' chip stock are significantly lowered, creating a risk of shortage.

Another important problem in the Thunder Bay region comes from forest fires. When the forest fire risk provided by the daily forest fire danger advisories exceeds a certain level, all operations in the forest must be suspended. The forest fire season often begins in the spring and lasts until the end of summer. In 2005, there were 7438 forest fires reported in Canada, representing 1.7 million hectares, with an annual average over 10 years of 7493 forest fires, burning 2.5 million hectares (Canadian Interagency Forest Fire Centre 2006). These unpredictable interruptions also have a negative effect on the chip supply at the Bowater mills.

The adoption of the just-in-time supply management system has made Bowater's Thunder Bay paper mills highly dependent on the sub-contractors supplying the chips. Given that each of the sub-contractors is paid a set price per volume unit delivered, the sub-contractors generally endeavor to produce the maximum amount of chips possible in a given lapse of time in order to make their forest operations as profitable as possible. However, since the primary materials supply is adjusted almost in real time according to market demand, many of Bowater's sub-contractors are paid only when the mills receive chips of the desired wood variety, which causes discontent among some of the sub-contractors. Clearly, Bowater's new supply management system means that the sub-contractors must make frequent unexpected trips to fulfill the mills' needs. Sometimes, before even finishing with a series of cutting blocks to fulfill a previous demand for a certain wood variety, the sub-contractors must move all their equipment to another site in order to cut the variety now required by Bowater, if the new variety is not found in the block currently being cut or if it is found in insufficient quantities. The travel distance from one cutting block to another often engenders significant extra access costs, primarily for fuel and paid travel time.

In addition, the Bowater Thunder Bay mills now require the different wood varieties to be separated. This additional requirement was not in effect when in-woods chipping operations were begun, and the need to separate the chips by variety has caused an increase in the number of equipment transfers over the last several years.

3.2. In-woods chipping

The supply method currently employed by Bowater and its private sub-contractors in the Thunder Bay region is primarily in-woods chipping. This harvesting method proceeds in multiple steps (Favreau et al. 2005). First, there is the felling-grouping activity, which consists of identifying and separating the different varieties requested (i.e., black spruce, jack pine, birch, poplar, or aspen) from the varieties available. Then the felled trees are skidded using a grapple vehicle. The piles of softwood (black spruce and jack pine) are transported to delimbing zones, while the piles of hardwood (birch, poplar, and aspen) are placed at least 100 meters from the chipping zones for later processing. Delimbing is only done for the softwood trunks containing sections destined for veneer production. These sections will later be transported directly to one of the two Bowater sawmills. The trunks that are too small or that have defects are not delimbed and are chipped as they are. A second phase begins with the delimbing-debarking-chipping (DDC) operations for the hardwood trees previously felled and transported and those softwoods that were not transported to the sawmills. The DDC activity is the final step in the in-woods chipping operation. The chips produced on-site in the forest are then sent to the Thunder Bay mills on a type-B tractor-trailer truck.

The principal advantage of using in-woods chipping (Favreau 1992) is that the cost of transporting the chips with the type-B tractor-trailer truck is less than the cost of transporting logs with a typical 48-foot 5-axle trailer, regardless of the distance. In addition, in-woods chipping is more productive than the use of satellite yards for small-diameter trunks, because the DDC machines are able to process several small-diameter trees at the same time.

Nonetheless, in-woods chipping does have its disadvantages. First of all, in certain harvesting regions, the cost of constructing and maintaining the roads is quite high, which makes it difficult to modify the road network to allow the DDC machines to pass through. Second, harvesting small surface areas with few trees means that the DDC machines must be moved frequently, which can increase costs significantly. Finally, some mills may refuse chips produced in-woods, judging their quality unsatisfactory. This inferior quality is primarily due to the lack of efficiency of the debarking technology used in the mobile equipment, compared to the technology used in the stationary equipment used in satellite yards.

3.3. Satellite yards

Satellite yard operations are quite simple. Once a cutting sector has been assigned to a satellite yard, Bowater's Thunder Bay sub-contractors need only perform the first three activities of in-woods chipping in the forest: felling-grouping, skidding and delimbing. The logs are then transported by 48-foot 5-axle trailers and grouped and stored by variety in the courtyard of the satellite yard.

When the pulp and paper mills at Thunder Bay need chips of a given variety of wood, the mill calls the sub-contractor who then goes to the satellite yard and chips the quantity of wood needed to fulfill Bowater's demand. So that such chipping on demand can be accomplished, one or more permanent production lines are kept available, allowing high quality wood chips to be produced in very little time. These lines include a stationary loader at the entrance to the mill, one or more conveyors, a residue grinder, one or more debarkers, and one chipper. The wood chips are then loaded onto a type-B tractor-trailer truck and transported to the Thunder Bay mills.

The advantages of setting up satellite yards are numerous (Favreau 1992). First of all, it is clear that, starting from the moment when Bowater issues the demand, the average time for supplying chips to the pulp and paper mills at Thunder Bay is reduced, given that the stock of logs is already at the satellite yard. This ready availability allows Bowater to reduce the amplitude of the negative consequences of a chip shortage at the Thunder Bay mills, since the situation can be rapidly remedied. The production of the Bowater mills is thus protected to a certain degree from the upsets caused by forest fires, droughts, or heavy rains. Setting up satellite yards also allows the regularity of the chip supply to be better insured, since the transport between satellite yards and the pulp and paper mills at Thunder Bay are affected little, or not at all, by the reduced trailer loads during the spring thaw. This could allow transportation costs to be reduced, compared to in-woods chipping operations.

Another advantage of satellite yards is that there are fewer harvesting machine transfers to be executed, since in most cases, the contractors no longer need to move their equipment rapidly from one cutting sector to another when Bowater requires chips from a wood variety found in quantity in a different cutting sector. Clearly, with satellite yards and log storage in the Thunder Bay mills' courtyard, sub-contractors can now complete the harvest in one cutting sector before moving to another. This allows them to plan their movements in the forest more efficiently, reducing the number of trips and thus the cost of wood chip production. In addition, reducing the number of harvesting machine transfers will consequently reduce the number and size of the ruts produced in the logging roads.

Since satellite yard production lines are stationary, chipping equipment handling is practically eliminated. The fact that the yard conveyors permit a better alignment of the log when it is introduced into the chipper also reduces the risk of equipment breakdowns. Similarly, it is easier to organize and respect the time periods for preventive maintenance, since the log stock is already available at the satellite yard. For example, if Bowater requests wood chips during the scheduled maintenance period of the felling and grappling equipment, this maintenance can still take place because this equipment isn't needed to fulfill the demand since the log stock is already available. Furthermore, if equipment breaks down, the time required to repair it is greatly reduced since all the tools needed are readily available at the satellite yard. An added advantage of using satellite yards is a higher quality of wood chips resulting from better chip quality control.

Despite this long list of advantages linked to satellite yards, there are still some disadvantages. First, the contractors must deal with the regulations governing wood residue storage. With in-woods chipping, this residue is distributed throughout the cutting sectors, but with satellite yards, it is concentrated at the mills and must be dealt with by the contractors. However, given that a large portion of this residue comes not only from the bark of the tree trunks, but also from the fibers lost during production activities, one possible solution to the residue problem would be to use the residue to produce energy for a part of the satellite yard's operations. A second disadvantage is the additional loading and unloading operations that are added to the supply activity, due to transporting the logs from the cutting sector to the satellite yard. To these extra handling activities must be added the waiting time before each loading/unloading operation and the risk of keeping too much log stock on hand, which could reduce the freshness of the wood.

4. Mathematical model

The following mixed-integer linear programming model was used to solve the Capacitated Facility Location Problem for satellite yards.

4.1. Defining the parameters and the variables

Several sets, parameters and variables were required to solve the facility location problem for satellite yards. We considered a set I of cutting sectors, where $I = \{1,2,\ldots,m\}$; a set J of potential sites for setting up a satellite yard, where $J = \{1,2,\ldots,n\}$; and a set K of types of wood, where $K = \{1,2,\ldots,o\}$. The annual tonnage of type k logs supplied from cutting sector i is designated by the parameter t_{ik}. The cost c_{ijk} represents the cost of harvesting, transporting, and transforming one ton of type k logs, with transport from cutting sector i to potential site j. The cost d_{ik} represents the cost of harvesting and in-woods chipping for one ton of type k logs at cutting sector i and transportation from this sector directly to the final destination (i.e., the pulp and paper mills at Thunder Bay). The cost h_{jk} is the cost of transporting one ton of chips of type k wood from potential site j to the mills at Thunder Bay.

The cost b_j is the annual capital cost related to opening a potential site j. This cost represents the annual depreciation of the set of fundamental costs. This heading includes the costs of preparing the terrain for a satellite yard: the earthworks at the site, the acquisition of a scale, the electricity to power the mill, and the cement flooring needed to store the chips and the residues. This heading also includes the baseline cost of installing a production line, comprising a stationary loader at the mill entrance, a residue grinder and a chipper. To this depreciation should be added the costs for licensing, insurance, maintenance and repairs. The cost f_j is the annual capital cost for each production line set up at a potential site j, including the cost of the debarkers and the conveyors, the licensing and insurance costs, and the maintenance and repair costs actually charged. The volume of the annual production capacity in cubic meters of wood for one production line at a potential site j is expressed as the parameter q_j. A maximum number r_j of production lines can be set up at any potential site j, and a maximum number p of satellite yards can be implemented.

The parameter g_e represents the annual cost of a number e of DDC machines used for in-woods chipping, and includes the annual depreciation of the DDC machines, the associated maintenance and repair costs, as well as the licensing and insurance costs. The parameter s_e represents the volume of the annual chipping capacity in cubic meters of wood for a number e of DDC machines. A maximum number l of DDC machines can be assigned to the entire group of cutting sectors.

The parameters α_k et β_k correspond, respectively, to the percentage of loss due to debarking type-k logs before their transformation into chips and the green density of type-k logs. Green density is expressed in tons of logs with bark per cubic meter of merchantable timber (i.e., without bark).

Our model uses six types of decision variables, four continuous and two binary. The variable x_{ijk} is the annual tonnage of type-k logs with bark transported from cutting sector i towards a potential site j. The variable u_{ik} is the annual tonnage of type-k logs with bark, chipped in-woods in cutting sector i and sent directly to the pulp and paper mills at Thunder Bay. The variable v_{jk} is the annual tonnage of type-k wood chips transformed at potential site j and sent to the mills at Thunder Bay. The number of production lines set up at potential site j is designated by the variable w_j. The binary variable y_j has a value of 1 if a satellite yard is set up at potential site j; otherwise, its value is 0. If there is a total number e of DDC machines used for in-woods chipping, the binary variable z_e is equal to 1; otherwise, it is equal to 0.

4.2. Formulating the mathematical model

Based on the variables and parameters defined above, our problem can be formulated as shown below.

Minimize

$$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ijk}x_{ijk} + \sum_{i\in I}\sum_{k\in K} d_{ik}u_{ik} + \sum_{j\in J}\sum_{k\in K} h_{jk}v_{jk} + \sum_{j\in J} b_j y_j + \sum_{j\in J} f_j w_j + \sum_{e=1}^{l} g_e z_e \qquad [1]$$

with the following constraints:

$$u_{ik} + \sum_{j\in J} x_{ijk} = t_{ik} \qquad \forall i \in I, k \in K, \qquad [2]$$

$$\sum_{i\in I}\sum_{k\in K} \frac{x_{ijk}}{\beta_k} \le q_j w_j \qquad \forall j \in J, \qquad [3]$$

$$w_j \le r_j y_j \qquad \forall j \in J, \qquad [4]$$

$$\sum_{j\in J} y_j \le p, \qquad [5]$$

$$\left(1-\alpha_k\right)\sum_{i\in I} x_{ijk} = v_{jk} \qquad \forall j \in J, k \in K, \qquad [6]$$

$$\sum_{i\in I}\sum_{k\in K} \frac{u_{ik}}{\beta_k} \le \sum_{e=1}^{l} s_e z_e, \qquad [7]$$

$$\sum_{e=1}^{l} z_e \le 1, \qquad [8]$$

$$x_{ijk}, u_{ik}, v_{jk}, w_j \geq 0 \qquad \forall i \in I, j \in J, k \in K, \qquad [9]$$

$$w_j \geq 0 \text{ and integer} \qquad \forall j \in J, \qquad [10]$$

$$y_j \in \{0,1\} \qquad \forall j \in J, \qquad [11]$$

$$z_e \in \{0,1\} \qquad \forall e = 1,2,\ldots,l. \qquad [12]$$

This model allows the sum of the total annual costs to be minimized. The first three terms of the objective function [1], respectively, express the total cost of transporting logs from the cutting sectors to the satellite yards; the total transportation cost from the cutting sectors, where the logs are chipped in-woods, to the mills at Thunder Bay; and the total cost of transporting the chips from the satellite yards to the Thunder Bay mills. The fourth and fifth terms represent the total set up cost of the satellite yards on the selected potential sites and the production line setup costs at these yards. The last term represents the total cost of acquiring the DDC machines used for in-woods chipping operations.

Constraints [2] indicate that logs from cutting sector i must be transformed in-woods, or at one or more satellite yards, or possibly using both methods. Given that the capacity of the satellite yards is limited, it is possible that one or more cutting sectors must be assigned to more than one satellite yard, in addition to using in-woods chipping. Constraints [3] ensure that the total tonnage of logs to be chipped assigned to a satellite yard j respects the yard's maximal capacity. Since the capacity of the facilities is common for all types k of wood and is expressed in cubic meters of merchantable timber, it is necessary to apply a conversion factor to variable x_{ijk}. These constraints also prevent a cutting sector i from being assigned to a satellite yard j that is not open. Constraints [4] play a dual role. They stipulate that a production line cannot be set up at a potential site j unless this site was previously selected for a satellite yard. In addition, they specify that the number of production lines that can be set up there must not exceed a maximum number r_j of lines. The ban on setting up more than p satellite yards is imposed by constraint [5]. Constraints [6] are transformation constraints. When contractors bring logs to a satellite yard, the bark must first be stripped in order to transform the rest of the log into chips. Since the bark represents an average percentage α_k of the log tonnage entering a site j, this means that, at the end of the process, the remaining percentage will be equal to $1-\alpha_k$. Constraint [7] plays the same role as constraints [3], but for the case of in-woods chipping operations. Constraint [8] means that it is possible to have a maximum number l of DDC machines for the entire set of cutting sectors. The non-negativity of the variables is expressed by constraints [9]. Constraints [10] are the integrality constraints for the variables w_j, while constraints [11] and [12] require that variables y_j and z_e be binary.

5. The solution procedure

In this section, we define the different data needed to solve the mathematical model. These data were given to us by FPInnovations – FERIC Division (Forest Engineering Research Institute of Canada). They constitute FERIC Division's realistic estimations, but do not correspond to the real Bowater data, which are confidential. The following sub-sections present the solution procedure.

5.1. Potential sites *j*

First, we solved the model taking a set of 10 potential sites into account. These sites, shown in Figure 3, were selected by the Bowater management team and FERIC Division.

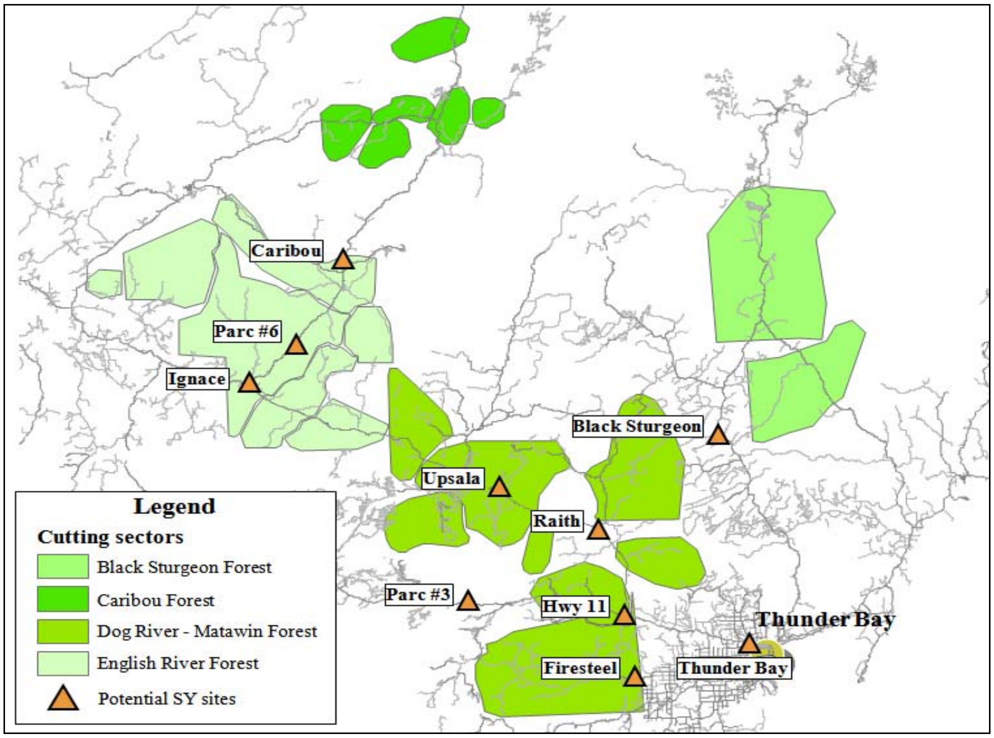

Figure 3: Map showing the cutting sectors, the 10 potential satellite yards (SY) sites and the Bowater Thunder Bay complex.

The second set of potential sites contained 127 sites, including the 10 potential sites mentioned above as well as 117 other sites. The additional sites that were selected from the set of sites are intersections where one or more public roads and one or more logging roads meet in proximity to or inside a cutting sector.

5.2. Types *k* of logs considered

The varieties of logs taken into account in the Bowater Thunder Bay problem fall into two groups: softwoods, including black spruce and jack pine, and hardwoods, including birch, poplar and aspen. The annual tonnages considered are the log tonnages supplied to Bowater's Thunder Bay pulp and paper mills in 2005.

In addition, to solve the problem, we considered that the humidity loss is the same whether the chips were produced in-woods or at a satellite yard. This hypothesis was put forward because, while there are many factors that can influence the percentage of humidity loss—storage time, temperature, sun intensity, and presence of rain—we felt that, though the logs stocked in the satellite yard's courtyard lost humidity while the log chipped in-woods lost none, the small variation in the humidity loss percentage would not affect the final solution.

5.3. Types of trailers used

In this study, we only considered two types of trailers: the 48-foot 5-axle trailer used to transport logs from a cutting sector to a satellite yard, and the type-B tractor trailer truck used to transport wood chips from a cutting sector or a satellite yard to the pulp and paper mills at Thunder Bay. Using these two trailer types is the most advantageous configuration for Bowater sub-contractors. However, this configuration does impose a capacity limit on the payload as well as a limit on the occupied volume. The capacities are provided in Table 1. These are the average limits and are representative of the measurements used in Thunder Bay. These limits were determined based on data in the FERIC Division database and discussions with various Bowater sub-contractors and with the Bowater Thunder Bay management team. The governmental regulations applied during the spring thaw were not taken into consideration when solving the problem. However, converting the capacity of the payload of each of the trailers, taking the density of the wood varieties into account, makes it obvious that even fully loaded, the trailers do not reach the maximum volume. Thus, only the mass acts as a constraint, for both hardwoods and softwoods. We also assumed that the mass capacity of the two trailer types is completely utilized.

Tables 2 and 3 show the average fuel consumption for the two trailer types, for public roads and logging roads and for empty and loaded conditions, respectively. The cost of fuel was set to $0.80/liter in our study.

Truck speed is limited by road conditions, whether the roads are public or logging, and whether the trailers are loaded or empty. The average speeds are shown in Table 4. These averages were determined beforehand from measurements taken by FERIC Division. Using a Global Positioning System installed in two trucks, each one equipped with a different type of trailer, the position and real speed of the trucks were recorded every 30 seconds. These data were recorded for a period of about two months. The data sets were cleaned manually before the data was processed and analyzed.

The loading, unloading and waiting times of the trailers at several points differ, depending on whether the chipping operations are conducted in-woods or at a satellite yard. These times are presented in Tables 5 and 6, respectively. The truck operating costs, including the trucker's salary but not the cost of fuel, was set at $53.20/hour.

The distances between the cutting sectors and the potential sites, as well as between these points and the Bowater complex at Thunder Bay, were calculated with the software Interface Map, a tool developed by FPInnovations – FERIC Division, using the shortest path function. For each distance, this software also indicated the portion of the route covering public roads and logging roads. We assumed that for each tour—from a cutting sector to a satellite yard, from a cutting sector to the Thunder Bay pulp and paper mills, or from a satellite yard to the pulp and paper mills—the departure point and the arrival point would be identical. For example, when a truck leaves a cutting sector to travel to a satellite yard, we assume that the truck must return to the cutting sector. Consequently, each tour is characterized by a loaded out trip and an empty return trip. Using the data presented above, we were able to calculate the different transportation costs c_{ijk}, d_{ik} and h_{jk}.

5.4. Setup, harvesting and transformation costs

We also considered that the satellite yard setup costs are invariable in terms of the potential site selected. In addition, we limited the number of production lines r_j to five for any potential site in order to keep the size of the different satellite yards set up relatively equal, as well as to prevent the network from becoming unbalanced. Each production line was considered to have an annual production capacity q_j of 250 000 m^3 of merchantable timber. The harvesting and transformation costs are independent of the cutting sector or the potential site assigned, but vary in terms of the production method (i.e., in-woods chipping or satellite yards). The costs are given in Tables 7, 8 and 9.

5.5. Solving the model using the solver, ILOG CPLEX 10.0.0

In order to transform the raw data into a model able to be solved with the commercial solver, ILOG CPLEX Interactive Optimizer 10.0.0, we used a program coded with Visual Basic 6.5. This program transformed the raw data into a linear model that was optimized by CPLEX. This model was then solved optimally.

The solution produced by solving the model indicates whether or not a cutting sector is assigned to one or more satellite yards, the satellite yards to which this cutting sector is assigned, and the quantity of logs of each wood variety assigned to each of these satellite yards. It is possible for a sector to be assigned to none of the satellite yards, in which case that sector will continue to be exploited using the current method, in-woods chipping. It is also possible for a cutting sector to be assigned to one or more satellite yards, but with a portion of its logs continuing to be chipped in-woods. In such a case, the solution indicates the quantity of logs that should be chipped in-woods, as well as the quantity of logs of each wood variety that is assigned to each of the satellite yards.

6. Solution and analyses

In this section, we present our analysis of the results from the model solved with the data for the 10 potential sites, as well as a sensitivity analysis of these data. Then, we present our analysis of the results from the model solved with the data for the entire set of 127 potential sites. Last, we compare our results with the solution obtained by FPInnovations – FERIC Division.

6.1. Analysis of the model results

In order to evaluate the viability of setting up satellite yards in the Thunder Bay region for use by Bowater's pulp and paper mills, we first had to determine whether such a project would be profitable, and then we had to quantify the annual profits that could be produced.

6.1.1. The scenario representing Bowater's current practices with its sub-contractors

This scenario represents the production method currently employed by Bowater and its Thunder Bay sub-contractors, as explained in section 3.2. No satellite yards are used, which means that the logs from all the cutting sectors are transformed (i.e., chipped) through in-woods chipping operations. The chips are then transported from the cutting sectors to the pulp and paper mills by means of type-B tractor trailer trucks. The results for this scenario represent Bowater's current situation at Thunder Bay based on the quantities of logs transformed in 2005. Table 10 shows the elements taken into account in the analysis: the total annual costs for transporting log and chips, the total annual costs of the different activities related to chip production, as well as the total annual costs related to acquiring the DDC machines and the other infrastructure needed to set up the satellite yards. The current scenario represents an annual cost of $27 410 245 for Bowater and its sub-contractors.

6.1.2. A general scenario representing the use of satellite yards

The general scenario represents the use of satellite yards and the assignment of each cutting sector to one or more of these yards. This production method is described in section 3.3. The solution obtained by solving the model for this general scenario reveals that the only potential site selected for a satellite yard is the one at Thunder Bay. This yard would have to include three production lines in order to satisfy the chip production needs. The quantities of logs (softwood and hardwood) from all 23 cutting sectors would be assigned to this satellite yard. The costs of the general scenario are provided in Table 11. The total annual cost of this solution is $25 557 868.

6.1.3. Comparison of Bowater's current situation with the general scenario

We can now evaluate the potential monetary gains of setting up satellite yards for sub-contractor chip production destined to supply Bowater's Thunder Bay pulp and paper mills. Figure 4 compares the various costs (in dollars) of the scenario representing the current situation and of the general scenario representing the use of satellite yards. The acquisition costs and other fixed costs represent only 65.8% of the costs of the current scenario. This means that it would be possible to save $495 443 annually by substituting the acquisition of DDC machines for the acquisition of the infrastructure needed to set up a satellite yard. Although the possible savings in total annual production costs with the general scenario constitute a reduction of only 7.5%, this slight percentage nonetheless represents $998 903. These savings come primarily from reducing by $3.30

the dollar cost per cubic meter for the harvesting operations shown in Table 9 by using satellite yards instead of in-woods chipping. With in-woods chipping, the sub-contractors must look for one wood variety at a time, which takes more time because they must first locate the variety and then fell the trees. Unlike in-woods chipping operations, satellite yards would allow the sub-contractors to fell several varieties at the same time and then sort them before transporting the log to the satellite yard.

The savings in terms of transportation costs with the general scenario are relatively small, only $164 910, or 1.96%. Despite reducing the total waiting, loading and unloading times from 3.05 hours to 2.16 hours per trip with the use of satellite yards, the sub-contractors still need to make more trips with the same number of trucks to supply the same quantity of wood chips, since they must also transport the bark which is still on the logs.

A comparison of Tables 10 and 11 shows that the cost of moving the DDC machines in the general scenario is nonexistent since the wood from all cutting sectors is chipped at the satellite yard. In addition, with the general scenario, $166 484 can be saved on logging road maintenance, though it will cost $99 890 more for clean-up at the cutting sites.

Combining all these elements, it appears that by promoting satellite yards over in-woods chipping operations, it would be possible to reduce the total annual costs by 6.76%. This reduction would constitute a significant sum for Bowater and its Thunder Bay sub-contractors: $1 852 377.

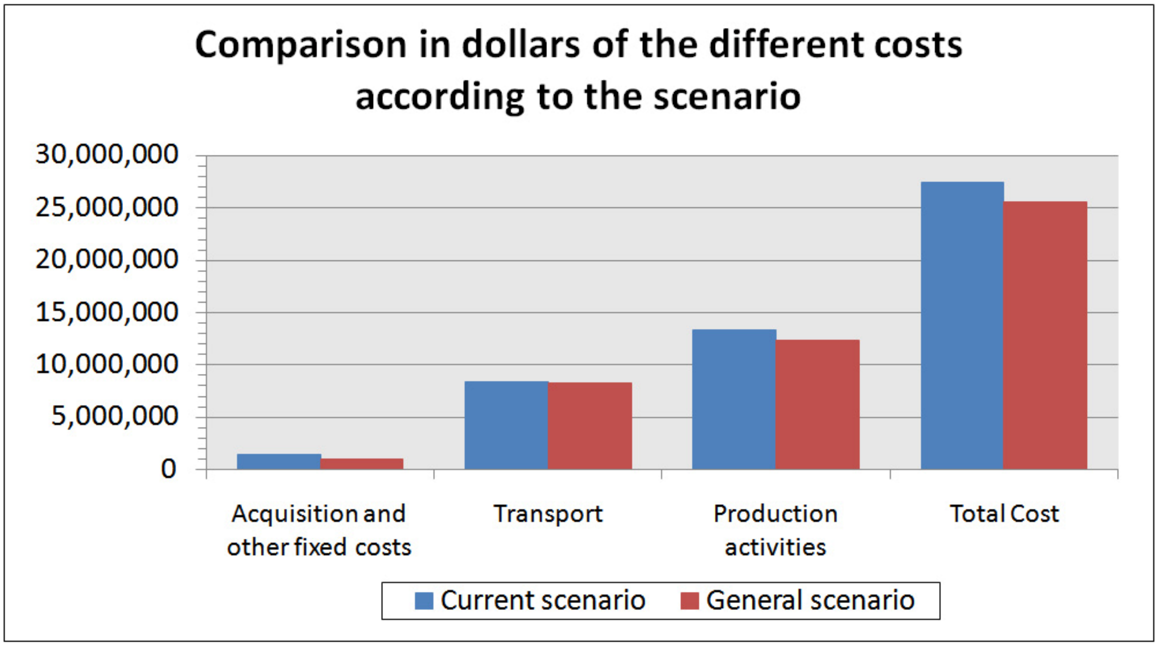

Figure 4: Comparison in dollars of the different annual costs for the current scenario and for the general scenario.

6.1.4. Sensitivity analysis

We judged it relevant to widen the scope of our analysis in order to verify the stability of the results obtained for the general scenario. We solved the same linear model, but modified the values of several important problem parameters in order to discover their impact on the general scenario results.

Scenario 1: Permission to open the potential Thunder Bay site is denied

First, we wanted to observe the repercussions that would occur if it was no longer possible to set up a satellite yard in close proximity to the Thunder Bay pulp and paper mills. This could happen, for example, if the town of Thunder Bay refused to authorize the construction of a satellite yard on the site in question. The solution for this scenario reveals that if the authorization was denied, two other potential sites would be selected for the satellite yard: Hwy 11 site and Black Sturgeon site. The satellite yard set up at Hwy 11 would have two production lines, while the one at Black

Sturgeon would only have one, since 21 of the 23 cutting sectors would be assigned in their entirety to the satellite yard at Hwy 11, whereas only the cutting sectors 22 and 23 would be assigned to Black Sturgeon. This solution represents a total annual cost of $26 041 472.

Scenario 2: Increase in the setup costs of the potential Thunder Bay site

Next, we increased the setup costs for the terrain at the potential Thunder Bay site by $2 500 000 in order to better reflect the reality of certain setup costs. In fact, FERIC Division evaluated the setup costs at this site to be quite high, notably because Bowater would have to acquire the terrains next to the pulp and paper mills, raze the buildings on these sites, execute the setup according to the standards of the town of Thunder Bay, which are stricter than those for an in-forest site, and pay higher property taxes. In addition, given that the Thunder Bay site is situated inside the town limits and about three kilometers from the Bowater mills, setting up a satellite yard in this place would not really be a satellite yard but a wood storage unit. For this second scenario, the solution and its costs are identical to scenario 1.

Scenario 3: Variation of the price of fuel

For the third scenario, three situations were studied. We first solved the model for a 25% reduction in the cost per liter of fuel, and then we solved the model for a 25% and a 50% increase. For each of these situations, the solution is identical to the one for the general scenario: a satellite yard with three production lines at the Thunder Bay site with all cutting sectors assigned to it. Given these results, it seems likely that even if the cost of fuel reaches $1.20/liter or goes down to $0.60/liter, the use of satellite yards recommended in the general scenario remains the most advantageous solution for Bowater and its Thunder Bay sub-contractors.

Scenario 4: Variation of loading, unloading and waiting times

For scenario 4, we evaluated four different cases. First, we increased by 50% the loading, unloading and waiting times connected to log transportation for the satellite yard production method. Then, we increased the times connected to wood chip transport by the same percentage. Finally, we solved the model by decreasing the times by 25% and 50% for the in-woods chipping method. The solution for each of these cases is the same as the one for the general scenario, except that the total annual costs of the first and second cases are respectively $26 133 077 and $25 844 420. These results mean that even if the loading, unloading and waiting times connected to in-woods chipping operations are reduced by half, the use of satellite yards remains the most advantageous plan for Bowater and its sub-contractors.

Scenario 5: Variation of the log tonnage

In the fifth scenario, we reduced the tonnage of logs from each of the cutting sectors by 25% and 50%. Then, we increased the tonnage by 25%, 50% and 100%. These variations allowed us to see the effects of varying log quantities.

In the two possibilities with reduced tonnage, the solution remains identical to the one for the general scenario, except that it is possible to have only two production lines instead of three. The same solution is produced when solving the model for the 25% and 50% increases in the log tonnages, but instead of three production lines, four lines must be set up at the Thunder Bay satellite yard. For the 100% increase, the model produces a solution requiring the opening of the Thunder Bay site and the Raith site, with three production lines at both sites in order to have enough capacity to produce the required wood chips. In this last solution, the total log tonnages from cutting sectors

14, 15, and 16, as well as 22 and 23, are assigned to the satellite yard at Thunder Bay, while the rest of the cutting sectors are assigned to the Raith satellite yard.

Scenario 6: Variation of the harvesting and transformation costs of the in-woods chipping production

Finally, for scenario 6, we evaluated the moment when in-woods chipping would become more profitable for Bowater and its sub-contractors, by varying the harvesting and transformation costs of this production method. To do so, we solved the model, diminishing the costs by 5%, 10%, 15%, 20%, and then 25%. Our results show that when the costs of harvesting and transforming the wood through in-woods chipping operations decrease by more than 15%, it becomes more advantageous to use the current in-woods chipping methods for all cutting sectors than to set up satellite yards. However, to reach such a cost decrease, Bowater and its sub-contractors would have to totally reorganize the in-woods chipping operations. Table 12 shows the different total annual costs according to the variation of the harvesting and transformation costs.

In general, we can conclude that the selections of the setup sites and the cutting sector assignments are quite stable. In fact, for most of the scenarios studied in the sensitivity analysis, the solution corresponds to the solution produced for the general scenario. It is only when the costs of harvesting and transforming the logs through in-woods chipping decrease drastically that this solution becomes less advantageous and, thus, undesirable.

6.2. Analysis of the model results for an extended set of potential sites

In order to verify whether or not the 10 potential sites selected by both FPInnovations – FERIC Division and the Bowater management team are in fact the best sites, we solved the model for the entire set of 127 potential sites. As indicated in section 5.1, the larger set of sites includes the first ten potential site considered in the solution process described above.

First, we solved the model a second time for the general scenario, but this time with the set of 127 potential sites. The solution produced is identical to the one found for the smaller set of 10 sites. Thus, we can conclude that, given the current parameters, the best solution is to set up a satellite yard with three production lines at the Thunder Bay site, located about three kilometers from the Bowater pulp and paper mills. The total tonnage of logs (both softwood and hardwood) from all of the cutting sectors will be transformed into wood chips at this site. This solution represents a total annual cost of $25 557 868 for Bowater and the sub-contractors concerned.

6.3. Comparison with the FPInnovations – FERIC Division solution

The solution proposed by FPInnovations – FERIC Division suggests a mixed assignment. FERIC Division recommends that a certain number of cutting sectors continue to use in-woods chipping, assigning other cutting sectors to one or more satellite yards. In the solution proposed by FERIC Division, four satellite yard sites are selected: Firesteel, Hwy 11, Upsala and Black Sturgeon. Each of these sites would have one production line. Table 13 summarizes FERIC Division solution.

Using the solution proposed by FERIC Division in our model, with the parameters of the general scenario, we obtained a total annual cost of $27 224 854, representing savings of $185 391, or a 0.68% reduction, compared to the current situation. Our solution represents savings of $1 852 377, or a reduction of 6.76%, compared to the total annual cost of the current scenario.

As Figure 5 shows, the difference in cost is primarily due to acquisition costs and other fixed costs. These costs reach $2 731 144 with the FERIC Division solution, while our solution only costs $954 789, a total of 65.04% less. This difference is caused by the fact that our solution uses only one satellite yard, while the FERIC Division solution uses four, each one with one production line. Given that setting up a new satellite yard costs three times as much as adding one production line to an existing satellite yard, our solution is less costly.

Still, we must point out that the FERIC Division solution has a lower total transportation cost than ours, for a difference of 2.83%: our transportation costs attain $8 227 730, while those for the FERIC Division solution are lower, $8 001 661. This difference can be explained by the fact that the satellite yards in the FERIC Division solution are closer to the cutting sectors that they serve. Clearly, it is less expensive to transport an identical initial given tonnage of wood in the form of wood chips than in the form of logs. Since the bark is taken off the log before it is transformed into chips, wood chip transport, unlike log transport, allows sub-contractors to reduce the transportation costs. The closer a satellite yard is to a cutting sector, the more the sub-contractors can avoid useless trips, since the bark is transported over a smaller distance.

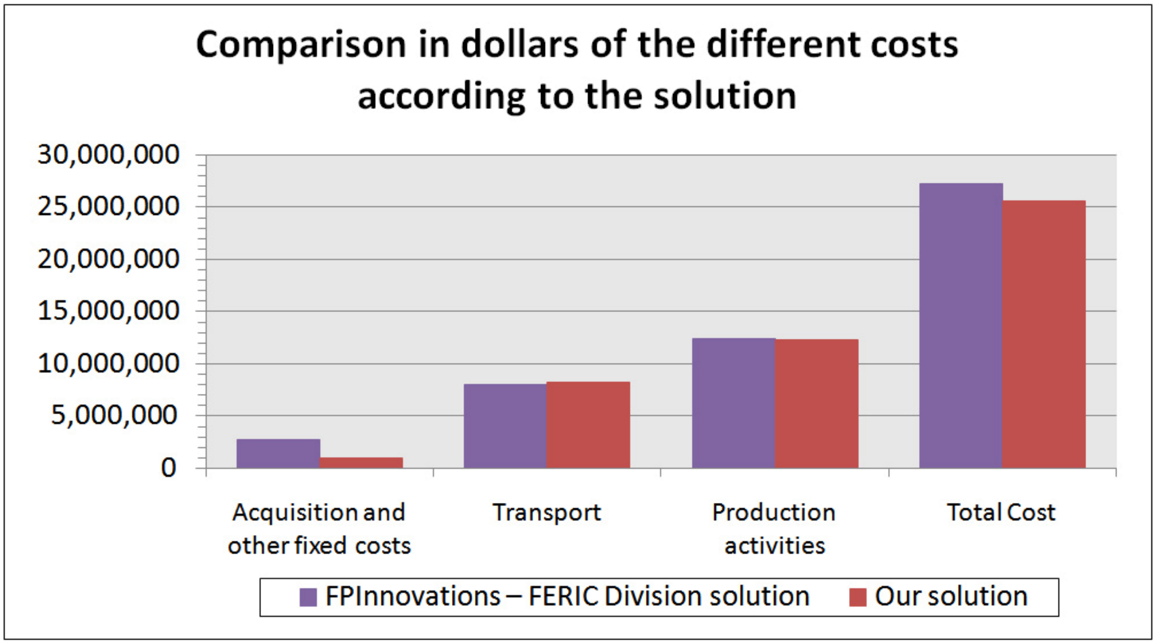

Figure 5: Comparison in dollars of the different annual costs of the solution proposed by FPInnovations – FERIC Division and our solution.

7. Conclusion

The problem that we studied was a concrete problem submitted to FPInnovations – FERIC Division by Bowater for inclusion in a study about the location of satellite yards in the chip supply chain of their Thunder Bay pulp and paper mills. This problem is a Capacitated Facility Location Problem, which we solved by developing a mixed-integer linear programming model. After describing the model in detail and solving it, we presented our analysis of the results obtained and studied diverse scenarios in order to observe the possible repercussions of certain model parameters on the solution. These analyses allowed us to identify the most propitious of the potential sites for the setup of satellite yards, as well as the assignment, or non-assignment, of each of the cutting sectors to these yards, while also minimizing the costs of production, transport and acquisition.

Acknowledgements

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Tables

Type of trailer	Payload (tons)	Volume (m^3)	In-woods volume (m^3)
A 48-foot 5-axle trailer	41.7	95.0	-
A type-B trailer truck	41.5	153.0	148.0

Table 1 : Trailer mass and volume capacities.

Type of road	Empty (liters/100 km)	Loaded (liters/100 km)
Public	37.0	81.0
Logging	50.0	114.0

Table 2 : Average fuel consumption of a 48-foot 5-axle trailer.

Type of road	Empty (liters/100 km)	Loaded (liters/100 km)
Public	38.0	82.0
Logging	48.0	119.0

Table 3 : Average fuel consumption of a type-B trailer truck.

Type of road	Empty (km/h)	Loaded (km/h)
Public	76.77	73.51
Logging	28.87	27.99

Table 4 : Average truck speeds.

Activities	Time (hours)
Waiting - forest	1.95
Loading chips - forest	0.69
Waiting - Thunder Bay	0.25
Unloading chips - Thunder Bay	0.16

Table 5 : Time spent loading, unloading and waiting with in-woods chipping.

Activities	Time (hours)
Waiting - forest	0.41
Loading log - forest	0.30
Waiting - satellite yard	0.41
Unloading log - satellite yard	0.30
Waiting - satellite yard	0.13
Loading chips - satellite yard	0.20
Waiting - Thunder Bay	0.25
Unloading chips - Thunder Bay	0.16

Table 6 : Time spent loading, unloading and waiting with satellite yards.

Infrastructure setup	Annual costs ($CA)
Opening of the site	406 293
One production line	182 832

Table 7 : Annual setup costs b_j and f_j for one satellite yard.

Number of DDC machines	1	2	3	4
Annual cost ($CA)	374 643	725 116	1 087 674	1 450 232

Table 8 : Annual acquisition costs g_e according to the number DDC machines necessary.

Activities	*IWC* ($CA/m^3)	SY($CA/m^3)
Felling	4.62	4.40
Transport to depot	6.95	3.65
Delimbing	0.00	5.35
IWC - Transformation into chips	8.47	0.00
Handling of the DDC machines	0.19	0.00
Maintenance of the logging roads	6.00	5.75
Clearing of the cutting sites	0.15	0.30
SY - Transformation into chips	0.00	5.14

Table 9 : Harvesting and transformation costs according to the production method, in-woods chipping (IWC) or satellite yards (SY).

Current scenario	
Activities	Annual cost ($CA)
Satellite yard - Transformation into chips	0
Satellite yard - Infrastructure and other costs	0
Satellite yard - Log transport	0
Satellite yard - Chip transport	0
Harvesting: Felling, skidding and delimbing	7 704 871
Logging road maintenance	3 995 612
Cutting sector clean-up	99 890
In-woods chipping - Transformation into chips	5 640 472
In-woods chipping - DDC machines and other fixed costs	1 450 232
In-woods chipping - Moving the DDC machines	126 528
In-woods chipping - Chip transport	8 392 640
Total	27 410 245

Table 10 : Total annual cost of Bowater's current scenario, using in-woods chipping only.

General scenario	
Activities	Annual cost ($CA)
Satellite yard - Transformation into chips	3 422 907
Satellite yard - Infrastructure and other costs	954 789
Satellite yard - Log transport	7 554 934
Satellite yard - Chip transport	672 796
Harvesting: Felling, skidding and delimbing	8 923 533
Logging road maintenance	3 829 128
Cutting sector clean-up	199 781
In-woods chipping - Transformation into chips	0
In-woods chipping - DDC machines and other fixed costs	0
In-woods chipping - Moving the DDC machines	0
In-woods chipping - Chip transport	0
Total	25 557 868

Table 11 : Total annual cost of the general scenario.

Variation	Production method	Total annual cost ($CA)
0%	Use of satellite yards only	25 557 868
-5%	Use of satellite yards only	25 557 868
-10%	Use of satellite yards only	25 557 868
-15%	In-woods chipping only	24 775 140
-20%	In-woods chipping only	23 896 771
-25%	In-woods chipping only	23 018 403

Table 12 : Total annual cost and most profitable production method according to the variation of the harvesting and transformation costs for in-woods chipping operations.

Cutting sector		Production method	Site
1	Caribou 6	In-woods chipping	-
2	Caribou 9	In-woods chipping	-
3	Caribou 11	In-woods chipping	-
4	Caribou 12	In-woods chipping	-
5	Caribou 13	In-woods chipping	-
6	Caribou 14	In-woods chipping	-
7	English River 18	In-woods chipping	-
8	English River 19	In-woods chipping	-
9	English River 37	Use of satellite yards	Upsala
10	English River 38	Use of satellite yards	Upsala
11	English River 39	Use of satellite yards	Upsala
12	English River 40	In-woods chipping	-
13	English River 41	In-woods chipping	-
14	Dog River 15	Use of satellite yards	Hwy 11
15	Dog River 16	Use of satellite yards	Firesteel
16	Dog River 17	Use of satellite yards	Hwy 11
17	Dog River 23	Use of satellite yards	Hwy 11
18	Dog River 25	Use of satellite yards	Upsala
19	Dog River 26	Use of satellite yards	Upsala
20	Dog River 42	Use of satellite yards	Upsala
21	Dog River 46	Use of satellite yards	Hwy 11
22	Black Sturgeon 161	Use of satellite yards	Black Sturgeon
23	Black Sturgeon 162	Use of satellite yards	Black Sturgeon

Table 13 : Solution proposed by FPInnovations – FERIC Division.