Analyzing the Impact of Implementing a Logistics Center for a Complex Forest Network

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Analyzing the Impact of Implementing a Logistics Center for a Complex Forest Network

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ABSTRACT

The challenges faced recently by the North American forest products industry have forced it to review many of its key operations. Implementing logistics centers for such a context may therefore help in allocating the wood fibre more efficiently and in reducing sorting and transportation costs. This paper aims to better understand the interaction between a forest logistics center and a complex forest network while exploring the business environment favoring the use of such a structure. A profit maximization model is proposed and applied to a real case in the Mauricie region in Quebec, Canada. A total of 18 groups of scenarios are tested, based on the use of a sort yard and of backhauling. Results show that a logistics center already in operation adds $0.52 in profits for each m$^3$ of wood available for harvest (over 2,580,411 m$^3$ per year) for the network under study ($1.4 million annually). A sensitivity analysis also highlights that higher prices and sorting error rates have the greatest impact on the logistics center’s profitability.

Key words: logistics centers, forest network, backhauling, sorting yards, supply chain management and design.
INTRODUCTION

The forest products industry in North America has been facing important challenges in the past few years with the Housing crisis of 2008-09 and the decline of the pulp and paper sector (Turkel 2017, Marowits 2010). Demand for certain products, such as lumber, has recovered but for others, the decline continues. Maximizing value from mixed-natural forest stands is important, as the logs harvested from these areas have a large range of values and are transformed by mills with very different processing capacities. In addition, in Canada, harvesting sites can be a long distance from the plant, and be distributed over different areas. Hence, it is hypothesized that logistics centers in the forest sector can help in allocating efficiently the wood fibre to the right users while reducing sorting and transportation costs. For the rest of this article, we shall refer to logistics centers as the simultaneous use of specific log sort yards and transportation coordination.

Some of the conditions for the success of a forest logistics center are low sorting errors (Sessions et al. 2005) and access to specific truck configurations (Chan et al. 2009). Nevertheless, there exists no consensus regarding the profitability of such structures nor a clear indication of the key factors defining their benefits. In addition, the interaction between forest logistics centers and their business environment are not often studied for a complex network. The goals of this paper are therefore to better understand the interaction between a logistics center and a forest network encompassing different mills as well as to identify the business environment that would favor the use of such a structure.

Data furnished by companies located in the Mauricie region in the Province of Quebec (Canada) are considered in this study. This network processes a large diversity of wood species. A logistics center is already in operation within the network, but it has a limited capacity and it only sorts hardwood. Furthermore, the location of this yard is on the periphery of the network’s center of gravity. This leads us to postulate that...
increased benefits are possible if a proper logistics center was optimally positioned in relation to the species and mills location in that network. This paper therefore also aims to identify the factors which have the greatest impact on the profitability of such a center in this context. Eight network configurations with four different potential sort yards were tested, along with a scenario without a sort yard to establish a comparison point and measure their profitability.

In the current scenario, the existing yard in operation in the northeastern part of the region was found to provide $0.52/m^3 increase in profit over all the wood available for harvest in the region (2,580,411 m$^3$ annually) when compared to a scenario with no yard being used. The addition of a second sort yard more to the south and next to a softwood sawmill led to a profit improvement of $0.22/m^3 for a total of $0.74/m^3. The use of backhauling brings an extra gain between $0.12 and $0.20/m^3, depending on the network configuration. The effect of five factors on the profitability of the proposed center was also explored: fuel costs, loading and unloading costs, sorting error rates, level of stumpage fees (royalties paid for wood use) and prices. Three network configurations, each with or without the possibility of backhauling, were selected to conduct a sensitivity analysis. Results showed that higher prices followed by higher sorting error rates (for sorting done at the landing or the mills), lower levels of loading costs and stumpage fees can increase the positive effect of sort yards. This result can help members of the forest industry to make better decisions regarding the implementation of a logistics center in a given region. This paper also contributes to the academic research by describing the dynamic of such a center in a complex network while proposing a profit maximization model that takes into consideration an extensive number of costs and factors as well as the effect of age on the value and density of wood.
The rest of this paper is structured as follows: first, a look at the scientific literature pertaining to logistics centers and how they are used as sort yards in the forest industry is proposed. Afterwards, a description of the methodology and the model are provided. The next section presents the results obtained, for both the base scenario and the sensitivity analysis. A conclusion ends the paper.

LITERATURE REVIEW

Most papers dealing with the concept of a logistics or a cross-docking center are actually exploring the effects of consolidation/distribution centers located in the downstream part of a value creation network. These centers are largely based on the principle of a transportation hub (Langevin & Riopel, 2005), which allows savings on transportation costs and delivery times by consolidating shipments (for an overview of distribution problems in logistics, see Yang (2013) and Olhager et al. (2014)).

Logistics centers in the forest sector take the form of sort yards. While products are consolidated in a typical distribution center, wood in a sort yard is separated into logs of different qualities, as the forest industry uses divergent processes (which produce sub or co-products). Sort yards are therefore used in the upstream part of the supply chain, contrary to logistics centers observed in other industries. They reduce sorting errors (Sessions et al. 2005) and optimize wood allocated to mills (Alam et al. 2014) to maximize value creation (Han et al. 2011) and allow for the use of oversized trucks (Sarrazin et al. 2018).

There are however three main drawbacks to using a dedicated sort yard: a rise in handling costs (Dramm et al. 2002), fewer direct deliveries to the mills (Sessions et al. 2005) and yard implementation costs (Chung et al. 2012). These can explain why sort yards are not always profitable. For instance, Sessions et al. (2005) found that using a sort yard was not advantageous in the region of British Columbia (Canada) they studied.
because of implementation costs as well as higher transportation and handling costs. However, they did not consider the cost of processing missorted wood. For their parts, Shahi & Pulkki (2015) simulated a sort yard in Northwestern Ontario that proved to be unprofitable in a network that had one product and one sawmill.

Amongst the references where the concept of a dedicated sort yard was found to be profitable, Keron (2012) developed a profit maximization model, which included harvesting, transportation and sorting operations as well as the implementation of a sort yard. The author evaluated that implementing a yard would add around $1 million in profits annually. For their part, Abasian et al. (2017) presented a mixed-integer programming model to optimize a forest biomass value chain with the possibility of using backhauling and installing an in-transit log yard (with no sorting at the log yard) as well as a pellet mill. They integrated harvesting, sorting, production and transportation costs and showed a potential 23% profit improvement. Finally, Sarrazin et al. (2018) developed an optimization model encompassing all costs up to the transformation mill as well as the revenues while allowing for the use of backhauling. A sort yard brought a profit increase of $0.50/available m³. Through a sensitivity analysis, they established that four factors (transportation costs, distance to forest, number of oversized trucks, and the cost of sorting in the forests and at the mills), all had a significant influence on profit improvement. However, the fictitious network they generated for experimentations could not measure the impact of many elements related to the real forest industry, such as the amount of wood each mill can receive from individual forest management units.

To test the concept of a forest logistics center on a complex case and business environment, an optimization model representative of how the forest products industry operates in the Mauricie region of the province of Quebec was developed. This type of problem is a form of the multiple-commodity facilities location problem, which “involves the routing of several commodities to the sort yard locations and (...) transformation of the
commodity” (Sessions & Paredes, 1987). Since sort yards allow capturing a greater value from the resource, a profit maximization model is utilized. The next section presents the methodology used and the proposed model to attain the objectives of this paper.

**METHODOLOGY AND MODELLING**

**Methodology**

As this paper aims to better understand the interaction between a forest logistics center and multiple differentiated mills using the same resource as well as to explore the business environment that would favor the use of such a structure, an optimization model was developed based on the one proposed by Sarrazin *et al.* (2018). This model integrates harvesting, transportation, mill and yard capacity as well as mill assignment constraints and was adapted to manage the complexity of a region-wide forest network. Most of the data required for the model (including potential sites) were collected from different forest products companies in the Mauricie region in the province of Quebec, Canada, as well as from scientific sources. The remaining data was estimated based on various hypotheses. The model was then run to identify the amount of profit generated by each scenario (addition of a single or several sorting sites). The model validation included a feedback loop where the data and/or the model were modified until both an admissible and a realistic solution were obtained. The methodology is presented in the following sequence of steps.

- Mapping the forest network of the Mauricie region
- Data collection
- Model development
- Model validation
- Running the current scenario and the sensitivity analysis
- Compiling and analyzing results
- Statistical analysis
The effect of five factors on the profitability of different network configurations was tested in order to identify which ones have the most influence. The configurations being tested were the following: No yard (to establish a point of comparison), the current Vallières yard (which is the status quo scenario), and a combination of the Vallières yard and a new yard in Rivière-aux-Rats (the optimal configuration). The factors tested were fuel costs, the cost of loading and unloading trucks, sorting error rates (for sorting in the forest or the mills), stumpage fees and price levels. Error rates tested ranged between 1% and 10% for hardwood (a rate of 8% was used in the base scenario). Other factors varied from -50% to +50% of their base scenario value. A statistical analysis was latter performed. Once again, each configuration was tested with and without backhauling.

Specifically, the forest products companies in the area provided distances, harvested volume and government wood allocation to each of their mills for 2016. With this data, the harvesting capacity and the wood composition for each forest management unit (FMU) was defined, with a total of 5 160 822 m³ available for harvest over a two-year horizon (twice the annual amount). The database includes nine wood species. The production capacity for each mill was determined using the sum of wood assignments from all forest zones. Four FMU’s were included in our database (4151, 4251, 4351 and 4352). There are 11 mills in the network, including five sawmills, three pulp and paper mills, two veneer mills and one panel mill. A map of the region, including possible sort yard locations, can be seen in Figure 1. Softwood dominates in the North, while hardwood and mixed stands are concentrated in the South. Wood is allocated to different business entities, which are quite differentiated in the hardwood sector. They nevertheless collaborate with one another, especially in the La Tuque area where several mills use the services of a sort yard (Vallières site). Forest companies in the region are searching for solutions to operate in a context of interdependence when procuring from mixed forest stands, and better coordinate value creation in their territory.
A confidential report from *FPInnovations FERIC* (Michaelsen & Tran, 2008) provided projections for the implementation costs of a sort yard at $0.48 for each \( m^3 \) processed at the site (with inflation). Wood chipping costs were deduced from Constantineau & Lacroix (2012). Conversion rates between products entering and exiting sorting processes, the most recent stumpage fees, harvesting costs, product prices and harvesting capacities were calculated with the MÉRIS software used by the *Bureau de mise en marché des bois* (2018) of the government of Quebec, Canada. Wood density levels by species were obtained from Lemieux (2014) while their development over time was deduced by comparing the density for green and dry wood (*Engineering Toolbox*, 2018) and estimating the speed at which wood loses moisture (*Partenariat Innovation-Forêt*, 2015). Transportation costs were gathered from the *FPInterface* software developed by *FPInnovations* (FPInnovations, 2018). Finally, industry experts, including one of the original developers of MÉRIS, were consulted to understand and organize the data, as well as to validate that the model adequately represented forest operations in the region.

**Case study – Mauricie region**

The Mauricie region is located midway between Montreal and Quebec City in the province of Quebec, Canada. It has some mixed forest stands, especially in the southern part of the region. It also has a functioning sort yard, called “Vallières” in the north, near La Tuque (Town of La Tuque, 2017). It has an annual sorting capacity of 400 000 \( m^3 \) and only processes hardwood. Two of the softwood sawmills in the region (i.e. Parent and Rivière-aux-Rats) have access to oversized trucks, by being connected to the forest road network. According to industry managers in the region, B-Train trucks, which have lower costs than tractors with 4-axle semi-trailers, are not adequate for hauling directly from harvesting sites. Therefore, sort yards also open the door to a wider use of B-Trains.
MODELING AND ROUTE GENERATION

To analyze the interaction of a logistics center with a complex forest network and how its profitability is influenced by its business environment, we built a mathematical model adapted from the one proposed by Sarrazin et al. (2018). The model maximizes network profits, i.e., revenues minus harvesting, stumpage, transportation, sorting, production, inventory and yard implementation costs. Decision variables concern quantities harvested transported, sorted, produced, inventoried and sold for each raw material or product, site, truck type, time period and client. A two-year time horizon of eight periods was used.

Mathematical modeling

The main elements included in the model are as follows:

Sets

- \( P^0 \): Set of products comprising wood chips and waste.
- \( PE, PS \): Set of products entering (PE), or exiting a process (PS).
- \( P \): Set of all products \( p \).
- \( S \): Set of all transformation processes \( s \).
- \( S_i^+ \): Set of all transformation processes \( s \) in which the site \( i \) is specialized (sorting for a yard, production for a mill).
- \( F \): Set of forest harvesting sites.
- \( Y \): Set of potential sites for a sort yard.
- \( M \): Set of mills.
- \( N \): Set of all sites \( i \) and \( j \) such as \( N = F \cup Y \cup M \).
- \( T \): Set of truck types \( t \).
- \( L \): Set of time periods \( l \) for the time horizon (including \( l = 0 \), to define a starting inventory).
- \( C \): Set of all clients \( c \).
- \( R \): Set of \( r \) routes.
- \( G \): Set of \( g \) wood families. It can include several species (for instance maple, birch, and softwood).
- \( U \): Set of \( u \) forest management units (FMU). Each FMU includes three or four forest zones.
- \( Log, log^+\), \( log^- \): Set of logs \( (log^- \)\), or wood that will later be sorted into logs \( (log^+ \). \( Log = log^+ \cup log^- \).
- \( A \): Set of possible ages \( a \). The age is calculated in time periods from the moment of harvest and can range from 0 to 8 periods, which is the length of the horizon.

Parameters

- \( E \): Volume capacity (in m\(^3\)) for a type \( t \) vehicle.
- \( Q_{ij}^t \): Weight limit (in tons) for a delivery with a type \( t \) vehicle between origin \( i \) and destination \( j \) (both \( \in N \)) during period \( l \).
- \( \Omega \): Fleet size of available type \( t \) vehicles.
- \( \beta^t \): Available time (in hours) on the road per month for a type \( t \) vehicle during period \( l \).
Variables

\( \eta_{il}^a \): Number of times that origin \( i \), and destination \( j \) (both in \( N \)) as well as a type \( t \) vehicle is en route \( r \).

\( W_r \): Number of hours required to travel on route \( r \) with a type \( t \) vehicle.

\( o^a, o^w \): Metric tons per m\(^3\) for product \( p \) with or without the age \( a \).

\( \delta^w \): Binary parameter determining if the weight limit applies to product \( p \) in period \( l \) or not.

\( c_{il}^p \): Stumpage fee (in \$/m\(^3\)) to be paid for product \( p \in \log^+ \), harvested at forest site \( i \in F \) and consumed by mill \( j \in M \).

\( d_i \): Harvesting cost (in \$/m\(^3\)) of product \( p \) at forest site \( i \in F \).

\( c_i^p, c_i^{+} \): Fixed cost (in $) for setting up yard \( i \) (\( c_i^p \)) and installation cost for a sorting capacity block at yard \( i \) (\( c_i^{+} \)).

\( c_{il}^{plt} \): Variable transportation cost (in \$/m\(^3\)) of product \( p \) from site \( i \) to destination \( j \) (both in \( N \)) during period \( l \) with truck type \( t \).

\( c_{il}^s \): Sorting or production cost (in \$/m\(^3\)) of using process \( s \) at site \( i \in N \).

\( c_{il}^{pld} \): Inventory cost (in \$/m\(^3\)) of product \( p \) at site \( i \in N \) during period \( l \).

\( c_i^e \): Fixed cost of route \( r \).

\( V_{ip}, V_{ip}^a \): Value (in $) of product \( p \) when sold to client \( c \) with or without the age \( a \).

\( Q, Q^+ \): Harvesting or process capacity for a capacity block at site \( i \) for the horizon \( (Q) \) or a period \( (Q^+) \).

\( Q_{il}^+, Q_{il}^{+} \): Extra capacity for the horizon \( (Q_{il}^+) \), or for a period \( (Q_{il}^{+}) \), and independent of capacity blocks.

\( Q_{il}^+ \): Harvesting capacity (in m\(^3\)) for period \( l \) for the entire network in m\(^3\).

\( Q_{il}^0 \): Estimated quantity (in m\(^3\)) of log \( p \) at forest site \( i \). Used for the accounting of stumpage fees.

\( W_{g_i}^a \): Amount of wood (in m\(^3\)) of group \( g \), from FMU \( u \) guaranteed to mill \( j \).

\( E_{ij}^l \): Volume capacity or space limit for inventory (in m\(^3\)) during a given period for site \( i \in N \).

\( \min, \max \): Minimum or maximum number of capacity blocks that should be installed at yard or mill \( i \) (also serves as the minimal percentage of wood to be harvested at forest site). Buying a capacity block gives the right to sort or process a certain amount of wood (typically 250,000 m\(^3\) for a sort yard).

\( g_{wy} \): Conversion rate between the quantity of products \( p \) and \( p' \) obtained in the sorting process \( s \).

\( T_{il}^\max \): Last period of the time horizon.

\( v^d \): Parameter expressing the minimal amount of production or sorting that has to take place at a given site \( i \in Y \cup M \) during period \( l \) (represents a percentage of its own average production).

\( z_i \): Binary parameter equals to 1 if sort yard or production site \( i \in Y \cup M \) is active, 0 otherwise.

\( \theta_{jpl}^p \): Binary parameter equals to 1 if product \( p \) enters a process used at mill \( j \in M \), 0 otherwise.
The objective function and the different constraints of the model are now described.

**Objective function:** \[
\text{Maximize} \quad \sum_{i} \sum_{c} \sum_{p} \sum_{l} \left[ \sum_{j} \sum_{r} c_{ij}^{pr} x_{ij}^{pr} - \sum_{j} \sum_{r} \sum_{l} \sum_{p} \sum_{l} \sum_{l} c_{ij}^{pr} x_{ij}^{pr} - \sum_{j} \sum_{r} \sum_{l} \sum_{p} \sum_{l} \sum_{l} c_{ij}^{pr} x_{ij}^{pr} \right]
\]

\[
- \sum_{i} \sum_{c} \sum_{p} \sum_{l} \sum_{j} \sum_{r} c_{ij}^{pl} q_{ij}^{pl} - \sum_{i} \sum_{c} \sum_{p} \sum_{l} \sum_{j} \sum_{r} c_{ij}^{pl} x_{ij}^{pl} - \sum_{i} \sum_{c} \sum_{p} \sum_{l} \sum_{j} \sum_{r} c_{ij}^{pl} x_{ij}^{pl} - \sum_{i} \sum_{c} \sum_{p} \sum_{l} \sum_{j} \sum_{r} c_{ij}^{pl} x_{ij}^{pl} - \sum_{i} \sum_{c} \sum_{p} \sum_{l} \sum_{j} \sum_{r} c_{ij}^{pl} x_{ij}^{pl} = (1)
\]

The objective function (1) maximizes profit, i.e., the sum of revenues from the sale of products minus costs related to harvesting, stumpage fees, sorting, production, transportation, yard implementation and inventory.

**Subject to:**

\[
Q_{i} \leq \sum_{p} \sum_{l} x_{ij}^{pl} \leq Q_{i} \quad \forall i \in F
\]

\[
\sum_{i} \sum_{c} \sum_{p} \sum_{l} x_{ij}^{pl} \leq Q_{i} \quad \forall l \in L
\]

\[
E_{i} \geq I_{i}^{pl} = I_{i}^{pl-1} + x_{ij}^{pl} + \sum_{s} \sum_{l} \sum_{p} \sum_{l} \sum_{l} q_{ij}^{pl} + \sum_{s} \sum_{l} \sum_{p} \sum_{l} \sum_{l} q_{ij}^{pl} - \sum_{s} \sum_{l} \sum_{p} \sum_{l} \sum_{l} x_{ij}^{pl} - \sum_{s} \sum_{l} \sum_{p} \sum_{l} \sum_{l} x_{ij}^{pl} \quad \forall i \in N, p \in P, l \in L | l \geq 1
\]

\[
I_{i}^{pl} \geq I_{i}^{pl'} \quad \forall i \in N, p \in P | l = l^{max} & l' = 0
\]

\[
Y_{i}^{pl} = \sum_{p \in P} \sum_{l} g_{i}^{pl} x_{ij}^{pl} \quad \forall i \in N, p \in PS, l \in L', s \in S
\]

\[
\min, n_{i} \leq z_{i}, \max_{i} \quad \forall i \in YUM
\]

\[
\sum_{i} \sum_{c} \sum_{p} \sum_{l} x_{ij}^{pl} \leq n_{i} Q_{i} + Q_{i}^{*} \quad \forall i \in YUM
\]

\[
\sum_{i} \sum_{c} \sum_{p} \sum_{l} x_{ij}^{pl} \leq n_{i} Q_{i}^{*} + Q_{i}^{*} \quad \forall l \in L, i \in YUM | l \geq 1
\]

\[
\sum_{i} \sum_{c} \sum_{p} \sum_{l} \sum_{j} \sum_{r} x_{ij}^{pl} \geq v_{i}^{pl} \sum_{i} \sum_{c} \sum_{p} \sum_{l} x_{ij}^{pl} \quad \forall i \in YUM, l \in L | l \geq 1
\]

\[
\text{Threshold}_{i} = \sqrt[\Theta]{\sum_{i} \sum_{c} \sum_{p} \sum_{l} x_{ij}^{pl}} \quad \forall i \in YUM, l \in L | l \geq 1
\]

\[
\sum_{r} (W_{ij} x_{ij}) \leq \beta_{ij} x_{ij}^{pl} \quad \forall i \in YUM, l \in L, t \in T | l \geq 1
\]

\[
\sum_{i} \sum_{c} \sum_{p} \sum_{l} x_{ij}^{pl} \leq \Omega
\]

\[
o_{i} q_{ij}^{pl} \leq \delta_{i} q_{ij}^{pl} + (1 - \delta_{i}) q_{ij}^{pl} E_{i} \quad \forall i \in N, j \in YUM, p \in P, l \in L, t \in T | l \geq 1
\]

\[
\sum_{p} q_{ij}^{pl} = \sum_{r} \sum_{l} q_{ij}^{pl} x_{ij}^{pl} \quad \forall i \in N, j \in YUM, l \in L, t \in T | l \geq 1
\]

\[
\frac{Q_{i}^{pl}}{Q_{i}} = \frac{Q_{i}^{pl}}{Q_{i}} \quad \forall i \in F, p \in P
\]
Constraint (2) establishes a harvesting capacity for the planning horizon and forces the system to harvest a minimal percentage of wood for each site (in this case, 90%). There is also a harvest limit for the whole network for each period (3). Constraint (4) represents an inventory capacity and flow conservation for each site and product. In order to guarantee that products can always exit the network, raw materials and intermediary products can always be “sold” for no revenue to a virtual client. This can be justified for some intermediary products, which have low value. Constraint (5) makes sure that the inventory for a product at a given site in the last period will always be equal to or higher than at the beginning of the horizon. This avoids having a starting inventory, which could be sold without involving costs. Constraint (6) establishes the relationship between the quantities of products entering and exiting any given sorting or production process.

Constraint (7) establishes a minimum and a maximum number of capacity blocks that can be used by a site (in the case study, 10 blocks of 250 000 m$^3$ were defined for each sort yard). Capacity blocks should not be confused with harvesting blocks which are geographical areas with a certain harvesting capacity. Constraint (8) establishes global sorting or production capacity limits for each yard and mill. Constraint (9) does the same for each period. Constraint (10) establishes a threshold of sorting or production to reach at the yards or mills to limit variations over time. Constraint (11) defines $Threshold_{il}$, which will be used later as a parameter to resolve the model again.
Constraint (12) ensures that the fleet of vehicles has sufficient time to achieve the routes being selected. Constraint (13) guarantees that the sum of trucks assigned to different bases is within the fleet size. Constraint (14) ensures that there will be enough volume or weight capacity for each truck to deliver the wood it was assigned to carry. Constraint (15) ensures that the number of deliveries per combinations of origin, destination, and truck type matches the number of times these combinations are in the selected routes. Constraint (16) ensures that there is consistency between the level of harvesting and the sum of logs originating from a forest site assigned to a mill. Constraint (17) specifies that the sum of logs assigned to a site must be higher than or equal to the sum of logs that was “sold” (for no revenue) or transformed at that same site. Constraints (18) and (19) guarantee that mills do not receive more than what they are entitled from each FMU and each product. Constraint (20) ensures that sort yards and mills will not eliminate intermediary products (only forest sites can do this). Variables are defined in (21).

To limit the size of the problem, the model was first solved without considering the effect of age. Groups of processes, which did not have at least one process used in this first solution, were next removed from the model. The model was then solved again, this time considering the impact of age on the network. Constraint (4) concerning flow conservation was replaced by constraints (22) and (23). Constraint (11) was also replaced with constraint (24) to use a predetermined level of production or sorting and limit resolution time. Finally, the objective function as well as constraints (5), (6), (8), (9), (10), (14), (17), (18), (19), (20) and (21) were modified with the age factor being added to the following parameters or variables: $o_{pa}$, $V_{pca}$, $q_{ij}^{pla}$, $x_{i}^{pla}$, $x_{i}^{pla}$, $z_{i}^{pla}$ and $l_{i}^{pla}$. Constraints (5), (6) and (20) were defined for $\forall a \in A$, while a summation over the age factor was added to all of these other constraints. There is also an age summation over the revenue, stumpage fee, variable transportation, sorting and inventory costs in the objective function.
Route generation

The general rule in the forest industry is to use full truck loads (FTL) with only one product being delivered at a time. As a result, a technique inspired by the MaxTour algorithm developed by Gingras et al. (2007) was applied to generate routes before the optimization takes place. This technique was itself an adaptation to FTL operations of the heuristic designed for less-than-truckload operations by Clarke & Wright (1964), where deliveries were merged together and where the most performing combinations were fed to the solver. In this way, a sizable number of delivery routes were generated. These routes respected the driving time limit of 14 hours while offering a certain cost saving as well as covering the entire network. We define a route as a sequence of one or more deliveries (from forest-to-yard, forest-to-mill or mill-to-mill). Each route starts from and ends at a vehicle depot or base.

RESULTS

Experimentation – Base scenario

Each forest zone considered in the model represents an aggregation of harvesting sites while only mills with at least 10 000 m³ of annual capacity and a significant level of interaction with the rest of the network were included in the database. Four different sites were identified as potential locations for a sort yard. One of them, the Vallières site, is already in operation. The other sites are Rivière-aux-Rats, near a softwood sawmill, Saint-Georges, which is close to a hardwood panel mill, and Saint-Tite (where no mill is located). Both Vallières and Rivière-aux-Rats can receive deliveries with oversized trucks. The possibility of enlarging the current Vallières yard (and allowing it to process softwood) was considered. The behavior of the network

1. \[ E_i \geq I_i^{pla} = I_i^{pl-laa-1} + x_i^{pla} + \sum x_i^{pla} + \sum q_i^{pla} - \sum q_i^{pla} - \sum x_i^{pla} - \sum x_i^{pla} \forall i \in N, p \in P, l \in L, a \in A | l & a \geq 1 \] (22)

2. \[ E_i \geq I_i^{pla} = x_i^{pla} + \sum x_i^{pla} + \sum q_i^{pla} - \sum q_i^{pla} - \sum x_i^{pla} - \sum x_i^{pla} \forall i \in N, p \in P, l \in L, a \in A | l \geq 1, a = 0 \] (23)

3. \[ \sum_{n \in N} \sum_{p \in P} x_i^{pla} \geq \text{Threshold}_i \forall i \in Y \cup M, l \in L | l \geq 1 \] (24)
with no sort yard was analyzed. Profit improvement using backhauling was also measured for each
configuration. Hence, 18 scenarios were tested. The model was implemented via the OPL Studio software
(version 12.6) and solved with the CPLEX solver. The total resolution times usually vary from 30 minutes to
an hour, depending on the complexity of the scenario. Table 1 presents all base scenarios.

As expected, the scenario with no yard or backhauling posted the worst results with a profit of about $1.8
million (Table 2). The configuration with two sort yards: one at the Vallières site and one in Rivière-aux-Rats
gave the best results, with a profit of $5.6 million (without backhauling). The amount of wood processed
when the two sort yards were operated reached 1 291 485 m³. About 80% of the wood processed in the yards
was hardwood (down to 50% in Rivière-aux-Rats). To have a stable point of comparison, the units used are
$/available m³, that is wood available for harvesting in the region over a two-year period.

Profit increases measured in $/m³ processed at the yards (without backhauling, see Table 3) stand between $2.15 (Saint-Georges only) and $3.32/m³ with the current Vallières yard. It reaches $2.95/m³ when both
Vallières and Rivière-aux-Rats are used. In that scenario, the two yards process fewer m³ (1 291 485) than
when they were operated separately and not simultaneously (800 000 + 1 000 000 = 1 800 000 m³). This is
because some of the wood is transferred from one yard to another as a new site is opened.

A closer look at the results of the base scenario (No backhauling, see Table 4) shows that the current Vallières
yard brings both higher revenues ($2.10/m³), but also higher costs ($1.58/m³). As harvesting levels go up,
this leads to more operations across the network (harvesting, stumpage, transportation, sorting, etc.). When a
yard is added in Rivière-aux-Rats, revenues increase by $0.30/m³ ($2.40 - $2.10 = $0.30/m³) and sorting costs go down by about $0.06/m³ ($0.46 - $0.40).

Backhauling analysis

The backhauling procedure allows combining two deliveries to reduce empty travel. It is seldom used in the Canadian forest industry, which means that trucks typically return to their point of origin empty. This raises the question of how much the use of backhauling could make the studied network more profitable. Increases in profit brought by backhauling are between $0.12 and $0.20/available m³. The most interesting options for backhauling tend to involve the Parent sawmill, located far from the others. In the most profitable route (used with an enlarged Vallières yard), the truck leaves the Vallières yard and goes to the 457-forest zone to pick up wood to be delivered to the Parent sawmill. The truck then picks up pulp and paper logs to be delivered to Trois-Rivières in the south. Around 35% of the costs ($493 per trip) are saved by combining these deliveries for total savings of $551 302 a year. Another good combination is to pair a delivery from the 457-forest zone to the Parent sawmill with a delivery from the nearby 459-forest zone to Vallières.

A dynamic effect was noted where the increase in profit obtained using backhauling was greater when a sort yard was used (by about 9-13%). This is true to a lesser degree when the Rivière-aux-Rats site is combined with Vallières (down to 4%), probably because of the greater use of oversized trucks. Although these vehicles bring lower transportation costs, they can travel on a limited set of roads. In addition, when Rivière-aux-Rats is used, the yard mostly processes softwood. Deliveries to the softwood pulp and paper mill (Trois-Rivières in the south) are difficult to combine since they involve longer travel times.
Sensitivity analysis

Higher fuel costs make the scenarios involving a yard less interesting while making the use of backhauling more profitable (Figure 2). This is because of the greater use of oversized trucks when a sort yard is used, which are quite economical for other transportation costs (loading and unloading costs, trucker salary and truck usage). This advantage is lessened by higher fuel costs as more direct routes tend to be used by regular trucks. This effect is less pronounced when a yard is operated in Rivière-aux-Rats, especially when backhauling is also used. The fuel cost in the base scenario was $1.20/litre for oversize and regular trucks.

Insert Figure 2 here

Increasing loading and unloading costs lowers the profit increases of all scenarios involving a sort yard (Figure 3). This is especially true in the scenario involving Rivière-aux-Rats, which, becomes comparatively less profitable than the current configuration as loading costs increase. Indeed, when this cost increases by 20% or more, it becomes more profitable to use backhauling with the current Vallières yard than to add a yard in Rivières-aux-Rats with empty returns. Loading/unloading costs are $3.00/m$^3$ for round wood (both oversize and regular trucks) and $1.80/m$^3$ for wood chips.

Insert Figure 3 here

Higher error rates (for sorting done at the landing or a mill) bring smaller profits for all network configurations, as more logs are misclassified. However, as can be seen in Figure 4, an increase of this factor has a positive impact on the gains that the sort yard brings (with or without the use of backhauling). A dedicated sort yard can sort wood with fewer errors, which offsets the negative effect of rising error rates. Hence, profits obtained in scenarios where a yard is used decrease less rapidly. Error rates have no impact however, on the profitability of backhauling. It was assumed that the error rate was the same at the landing and at the mills and that there were no errors when sorting was done at a sort yard.

Insert Figure 4 here
A rise in stumpage fees has a negative effect on the gains brought on by the different yards (Figure 5). As stumpage fees rise, logs that are more valuable become less profitable as a greater share of their value goes to the government. The Quebec government collects the fees since it owns most the forestlands (*Ministère des forêts, de la faune et des parcs* 2017), as opposed to companies. This offsets one of the advantages of using a sort yard: reducing sorting errors and capturing the full potential of the available wood. However, this trend slows down as stumpage fees increase beyond their level in the base scenario. At that point, harvesting levels tend to decrease especially in harvesting sites located in the south of the region, which do not have access to oversized trucks. This makes the use of a sort yard comparatively more profitable as both the Vallières and Rivière-aux-Rats sites have access to oversized trucks. They also make the use of B-Trains easier. In addition, as the share of wood being processed at the yards increases, sorting costs tend to diminish since sort yards have lower sorting costs. Together, these two factors partially mitigate the negative effect of higher stumpage fees.

Insert Figure 5 here

Obviously, higher prices paid for the final products make all scenarios involving a sort yard more profitable (Figure 6). The increase is especially important when a yard is operated at Rivière-aux-Rats. For both configurations involving a sort yard, profit increases accelerate for sales prices above their normal values in the current scenario. From this point, as prices increase, harvesting levels start to increase beyond the minimum for all scenarios (90%), especially when a yard is operated. Therefore, the higher prices apply to a larger volume of finished products, which creates this steeper rise of profit. Finally, backhauling does not have an impact on the results. This is because as prices increase, more and more origin-destination and truck-type combinations tend to involve longer distances as well as oversized trucks, which makes them more difficult to match with other deliveries and fit into the legal time limit.

Insert Figure 6 here
Statistical analysis

A multiple linear regression was performed using Minitab 18 to establish whether there is a significant correlation between profit improvement of each scenario and the five factors introduced in the previous section. In the regression formula below, \( y_i \) represents the variation of profits obtained in scenario \( i \), and \( \beta_{ni} \) represents the regression coefficients for the independent variables. The independent variables refer to the factors tested in the sensitivity analysis, namely:

\[ y_i = \beta_{o_i} + \beta_{1i} x_{1i} + \beta_{2i} x_{2i} + \beta_{3i} x_{3i} + \beta_{4i} x_{4i} + \beta_{5i} x_{5i} \]

Results obtained from the regression are shown in Table 5. All coefficients are in relation to a 1% variation in the value of the factor (as measured in the base scenario). When backhauling was used alone, fuel costs were the only factor to have both a meaningful coefficient and a p-value below 0.05. A single linear regression analysis was done to check the effect of one of the key parameters, fuel costs. The \( R^2 \) was still very high at 92.6%, confirming the results already obtained. For almost all of the other scenarios and factors tested, the p-values were below 5% (0.05). Another single linear regression analysis was done concerning the price factor and gave this factor a p-value of well over 0.05 at 0.37. The low p-value in the multiple linear regression was probably the result of overfitting. Prices have the highest coefficients in all scenarios involving a sort yard, followed by error rates. Load and unloading costs as well as stumpage fees also have a significantly negative impact whenever a sort yard is operated. For all factors, the difference between their coefficients when
backhauling is used or not is quite small. The p-values for the level of the fuel costs are all above 0.05, except for the scenario with only backhauling. It should however be mentioned that a single linear regression was conducted specifically for fuel cost which led to p-values well below 0.05 for all scenarios, except when the Rivière-aux-Rats yard was operated with the use of backhauling. The $R^2$ is also quite high for all scenarios, hovering between 86% and 94%.

Four of the five tested factors have a clear and significant impact on the profitability of a logistics center for the two most interesting sites, fuel cost being the only exception. Moreover, results show that sort yards can be quite profitable regardless of the level of variations. In addition, the coefficients for stumpage fees in the scenarios involving one or two sort yards are quite similar to one another. This leaves price levels as well as loading and unloading costs as the two most critical factors for both the profitability of the forest network and the concept of a new sort yard specifically in Rivière-aux-Rats.

**CONCLUSION**

The main objective of this paper was to understand the impact that the introduction of a forest logistics center in a complex and diversified forest network can have. No paper found in the literature included a mathematical model with a complete set of costs and a real forest network. This contribution includes a profit maximization model covering all relevant costs and a sensitivity analysis conducted over a complex forest network. Our experiment, using data from a real forest industry network, led to the identification of the optimal sites to install a sort yard. The interaction between a yard and the use of backhauling were quantified, and a sensitivity analysis regarding the effect of five environmental factors was performed. It was found that the existing yard (Vallières site) already contributes to around $0.52/available m$^3$ in profits, which amounts to about $1.4 million annually. The addition of a new sort yard in Rivière-aux-Rats would add another $0.22/m$^3$ (around $
0.55 million per year). Higher sorting error rates and a favorable market (with higher selling prices) tend to
make the use of a logistics center in the Mauricie region more profitable. On the other hand, loading costs and
stumpage fees make the use of a logistics center less interesting. While the factors that we tested (fuel cost,
loading cost, error rates, stumpage fees, product price) tended to have a significant impact on profitability,
the overall profit was quite robust. The mathematical model presented in this paper takes into consideration
an extensive number of costs and contextual factors that should prove useful for further research in forest
logistics.

The results presented in this paper relate to a specific forest network and uses a deterministic model, which
does not integrate the stochasticity of supply or demand. It would be relevant to test the model on different
geographical settings to verify how it would influence the profitability of a logistics center. The effect of other
factors, such as the level of implementation costs, the seasonality of demand and prices, forest composition,
the level of depreciation caused by the aging of the wood or the interaction with a biomass production mill
should also be looked at. Finally, for such a structure to be put into place, the issue of how to manage it would
need to be explored (mode of ownership, business model, profit sharing, etc.).

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Development grant (RGPIN/203193-2013). Moreover, special thanks to François Laliberté, ing.f., M.Sc. as
well as FPInnovations’ Francis Charette. We also want to acknowledge the help of the Groupe Initiative
Mauricie organization and its members, especially Carl Tremblay of Kruger and André Gravel of Domtar.
REFERENCES


**Table 1: List of all instances**

<table>
<thead>
<tr>
<th>Instance/Site/Backhauling</th>
<th>Vallières</th>
<th>Vallières with extra capacity</th>
<th>Rivière-aux-rats</th>
<th>Saint-Georges</th>
<th>Saint-Tite</th>
<th>Backhauling</th>
</tr>
</thead>
<tbody>
<tr>
<td>No yard</td>
<td></td>
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<tr>
<td>Vallières</td>
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<tr>
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<tr>
<td>Enlarged Vallières &amp; Backhauling</td>
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<td>Saint-Tite</td>
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<td>Vallières &amp; Saint-Tite</td>
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<td>Vallières &amp; Rivière-aux-rats</td>
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</table>
### Table 2: Network profits and profit increases by scenario (in $/available m³)

<table>
<thead>
<tr>
<th>Sorting facility</th>
<th>Transportation No Backhauling</th>
<th>Profit</th>
<th>Increase ($/m³)</th>
<th>Transportation Backhauling</th>
<th>Profit</th>
<th>Increase ($/m³)</th>
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</thead>
<tbody>
<tr>
<td>No Yard</td>
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<td>$1,836,091</td>
<td></td>
<td>$2,449,736</td>
<td>+ $0.12</td>
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<tr>
<td>Saint-Georges only</td>
<td></td>
<td>$2,269,116</td>
<td>+ $0.08</td>
<td>$2,972,035</td>
<td>+ $0.22</td>
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<tr>
<td>Saint-Tite only</td>
<td></td>
<td>$2,293,304</td>
<td>+ $0.09</td>
<td>$3,020,082</td>
<td>+ $0.23</td>
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<tr>
<td>Current Vallières Yard</td>
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<td>$4,496,029</td>
<td>+ $0.52</td>
<td>$5,526,066</td>
<td>+ $0.71</td>
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<td>+ $0.74</td>
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<td>Vallières + Saint-Tite</td>
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<td>$5,659,824</td>
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<tr>
<td>Rivières-aux-rats only</td>
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<td>$5,742,880</td>
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<td>+ $0.58</td>
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<td>Vallières + Rivière-aux-rats</td>
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<td>$5,646,198</td>
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<td>$6,457,161</td>
<td>+ $0.90</td>
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### Table 3: Profit increase per scenario ($/processed m³)

<table>
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<th>Sorting</th>
<th>$/m³</th>
<th>m³ processed</th>
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<td>No Yard</td>
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</tr>
<tr>
<td>Saint-Georges only</td>
<td>$2.15</td>
<td>201 403</td>
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<tr>
<td>Saint-Tite only</td>
<td>$2.21</td>
<td>207 141</td>
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<td>Current Vallières Yard</td>
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<tr>
<td>Vallières + Saint-Tite</td>
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<td>1 291 485</td>
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</table>
Table 4: Increases in revenues and costs (in $/available m\(^3\))

<table>
<thead>
<tr>
<th>Revenues &amp; Costs/Scenarios</th>
<th>Vallières</th>
<th>Vallières &amp; Rivières-aux-rats</th>
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<tr>
<td><strong>Revenues</strong></td>
<td>$ 2.10</td>
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</tr>
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<td>Harvesting/Stumpage</td>
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<td>$ 0.53</td>
</tr>
<tr>
<td>Sorting/Production</td>
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<td>$ 0.40</td>
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<td>Transportation</td>
<td>$ 0.66</td>
<td>$ 0.63</td>
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<td>Yard Implementation</td>
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<td>Inventory</td>
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<tr>
<td><strong>PROFITS</strong></td>
<td>$ 0.52</td>
<td>$ 0.74</td>
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### Table 5: Results of a linear regression for values of five factors over three configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Factor/R²</th>
<th>Empty Returns</th>
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<th>Backhauling</th>
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<tr>
<td></td>
<td></td>
<td>Coefficient</td>
<td>p-value</td>
<td>Coefficient*</td>
<td>p-value</td>
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<td>-</td>
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<td>$ 0.0434</td>
<td>0.000</td>
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<tr>
<td>Fuel costs</td>
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<td>-</td>
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<tr>
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<td>-</td>
<td>-</td>
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<tr>
<td>Error rates</td>
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<td>-</td>
<td>-</td>
<td>$ 0.0000</td>
<td>0.185</td>
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<tr>
<td>Stumpage fees</td>
<td></td>
<td>-</td>
<td>-</td>
<td>$ 0.0000</td>
<td>0.820</td>
</tr>
<tr>
<td>Prices</td>
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<td>-</td>
<td>-</td>
<td>$-0.0001</td>
<td>0.001</td>
</tr>
<tr>
<td>Adjusted R²</td>
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<td></td>
<td></td>
<td></td>
<td>94.0%</td>
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<td>Vallières</td>
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<td>Constant</td>
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<td>0.000</td>
<td>$-1.2650</td>
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<td>Fuel costs</td>
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<td>$-0.0002</td>
<td>0.883†</td>
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<td>Load &amp; Unloading costs</td>
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<td>0.003</td>
<td>$-0.0037</td>
<td>0.002</td>
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<td>Error rates</td>
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<td>Adjusted R²</td>
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<td>89.3%</td>
<td></td>
<td>90.2%</td>
<td></td>
</tr>
<tr>
<td>Vallières &amp; Rivière-aux-rats</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td></td>
<td>$-1.6640</td>
<td>0.000</td>
<td>$-1.6150</td>
<td>0.000</td>
</tr>
<tr>
<td>Load &amp; Unloading costs</td>
<td></td>
<td>$-0.0006</td>
<td>0.733†</td>
<td>$-0.0000</td>
<td>0.984</td>
</tr>
<tr>
<td>Error rates</td>
<td></td>
<td>$ 0.0054</td>
<td>0.002</td>
<td>$ 0.0052</td>
<td>0.004</td>
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<tr>
<td>Stumpage fees</td>
<td></td>
<td>$-0.0039</td>
<td>0.026</td>
<td>$-0.0042</td>
<td>0.017</td>
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<tr>
<td>Prices</td>
<td></td>
<td>$ 0.0281</td>
<td>0.000</td>
<td>$ 0.0287</td>
<td>0.000</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td></td>
<td>86.5%</td>
<td></td>
<td>86.7%</td>
<td></td>
</tr>
</tbody>
</table>

* Coefficients represent profit increases relative to 1% variations in comparison to the base scenario
† Results of a simple linear regression show that fuel costs have a significant impact for this instance
Figure 1: The Mauricie forest network with its 12 harvesting zones and 11 business units (mills) (Sources: © Gouvernement du Québec and Ministère des Forêts, de la Faune et des Parcs).
Figure 2: Effect of fuel costs on profit increases
Figure 3: Effect of loading and unloading costs on profit increases
Figure 4: Effect of sorting error rates (at the landing or the mills) on profit increases
Figure 5: Effect of stumpage fees on profit increases

Stumpage fee variations

- Vallières
- Vallières and Backhauling
- Vallières + Rivière-aux-rats
- Vallières + Rivière-aux-rats & Backhauling

Profit increase ($/available m$^3$)

$\text{Profit increase ($/\text{available m}^3$)}$

-50% -40% -30% -20% -10% 0% +10% +20% +30% +40% +50%
Figure 6: Effect of price variations on profit increases