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# Timber selling policies using bundle-based auction: the case of public forests in Québec

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**Abstract.**

In the province of Québec, the government provides 25% of the volume of timber that is annually cut in crown forests through sealed-bid one-winner auctions. It was noted that many offers are made for some areas but few or none are made for many other areas. As such, a significant number of the timber volumes remains unsold. However, the combination of areas to form bundles can provide economy of scale that is not seen otherwise. We highlight some issues regarding the current allocation system and we analyse the effectiveness of different bundling systems in maximizing government revenues and enhancing bidders' competitiveness. We use actual forest data to evaluate different rules and strategies for the creation and allocation of partial and full bundles. Our results suggest that the use of the option of bundling forests areas makes the auction process more beneficial to the majority of stakeholders: Government revenues are increased; the bidding companies are more likely to obtain the desired volumes and pay less for harvesting and equipment relocation; and greenhouse gas emissions are reduced.

*Keywords:* Forest Industry, Auctions, Natural Resources, Québec

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## 1. Introduction

In the province of Québec, located in eastern Canada, a new forest regime has been in force since 2013. This regime fosters a competitive timber market for some of the wood available in public forests accounting for more than 90% of the forests in the province. So, the Québec Timber Marketing Board (TMB) was entrusted the responsibility to sell this wood through auctions. During the last five years, the TMB organized several rounds of auctions. At each auction, bidders can bid on as many items as they want, with one bid for each single item. Unfortunately, these rounds of auctions did not prove to be satisfactorily because the number of unsold timber volumes at the end of each round was too high. Therefore, in this article, we aim at improving the methodology for Québec timber sales on the open market using the concept of combinatorial auctions. This is expected to provide economy of scale and an increase in timber sales.

Combinatorial auctions allow bidders to form bundles of multiple heterogeneous items and bid on them. They are an extension to single-item bids, and should be considered when complementarities, indivisibilities, or other complications exist between the different items in a bundle (Jones and Koehler, 2002). They promote efficient pricing and allocation of bundles to bidders with respect to their budgets constraints (de Vries and Vohra, 2003; Zhou et al., 2015; Humphreys et al., 2007). Since the first model proposed by Rassenti et al. (1982), combinatorial auctions have received much attention as an allocation technique with different applications, such as airport landing slots, truckload transportation, and industrial procurement. Yet, less literature can be found on their application for natural resources. It is however known that combinatorial auctions have two challenging problems: (1) the bid generation problem, and (2) the winner determination problem. The resolution of these problems needs to be tailored to the specific details of the situation, and reflect the wider economic circumstances (Wang and Xia, 2005; Klemperer, 2002). In the context of a timber-selling system, it is necessary to consider the spatial nature of the problems. The sawmills and the forest areas are typically located in different regions. Resource constraints on some bidders usually limit the number of combinations bids that they will submit. For his part, the auctioneer needs to establish a true market value for the items sold in bundles. He could restrict the collection of bundles on which bidders might bid in order to overcome the bid generation intricacy, especially as the problem instance gets large. In fact, in mathematical terms, the problem becomes NP-hard, that is the problem cannot be solved in a short (polynomial) period of time (Rothkopf et al. 1998). It may however be solved efficiently by a mixed-integer programming (MIP) formulation. Such formulation (most often) only guarantee an optimal solution within some tolerances, i.e., by using bounds on the gap between current solution and a relaxed version of the problem (typically the LP-relaxation; a related linear programming problem that is solvable in polynomial time).

The paper studies two bundle-based bidding systems where companies are allowed to form their own bundles under certain constraints. In "full bundling", the bidder needs to bid on combinations of stands so that the total volume of the bundled stands covers the bidder's required wood supply through the auctioning system. However, this constraint is relaxed in "partial bundling" where several bundles of smaller volumes are allowed. We analyze the effectiveness of partial and full bundling systems in maximizing government revenues and enhancing bidders competitively. We use actual forest data to simulate and compare the rules that would most likely be put into practice by the TMB for bundles creation along with the auctioning strategies that can be employed by the forest products companies to within the limits of these rules. The remainder of the paper is as follows. In section 2, we present a background on auction systems for natural resources, and explain the current auction system implemented in Québec. Section 3 describes our methodological framework and includes an illustrative example. The case study is described in section 4 while the results are presented in section 5. Finally, section 6 concludes and provides directions for future research.

## 2. Background

### *2.1. Auction systems for natural resources allocation*

Auctions are defined as market techniques with predetermined set of rules in which bidders compete for the right of resource allocation and for prices (Mcafee et al., 1987). The literature identifies four types of auction, two open and two sealed, with First-price-sealed-bid (FPSB) auctions being the most widely used. Governments use them under different forms to transfer natural resources property rights from public to private control (Hendricks et al., 1993; Crowley and O'Connor,1993). For example, FPSB has been extensively used for allocation problems in the mineral industry (Milgrom, 1979; Milgrom and Weber, 1982) and the oil and gas sectors in the U.S. (Griffin, 2013).

Auction systems for timber allocation are used in many countries. In the United States, several state governments have historically employed both open and sealed bid auctions to sell timber from public forests. Also, an intricate debate on the design of federal timber auctions was early faced. After Mead (1967) published a study arguing that open auctions generate less revenue, the U. S. government proposed the use of sealed-bid auctions. However, forest managers were allowed to use open auctions if they could justify the choice. As a result, different systems were applied in different areas; however, sealed-bid auctions have attracted more small bidders. Recently, the decline in the U.S. stumpage prices has raised questions about the impact of state policies on the price paid for stumpage. According to Brown et al. (2012), more than sixty percent of the problem refers to state allocation strategies, including the auction method. Moreover, several market-based systems were introduced in Canada following a trade agreement with the U.S. in 2006. Farnia et al. (2013) designed and simulated a sealed first-price multiple round auction. More recently, Farnia et al. (2015) proposed a time-based combinatorial auction that takes in consideration the expected delivery period when allocating products to auction winners. According to the authors, this coordination among auction winners would improve the economic value obtained. Very recently, Boukherroub et al. (2017) proposed a sustainable framework for Canada timber allocation problem. The authors highlighted the importance of allocation strategy to guarantee fairness between forest companies in order to develop a sustainable public resource allocation. Empirical evidence on how the choice of auction conditions affect bidders' competition is scarce. In fact, many auction markets operate under a given set of rules rather than experimenting with alternative designs. Generally, revenue differs among auction types because of differences in the ability to observe market signals. Theoretical models predict that the English auction is more vulnerable to collusion than sealed biddings (Miller, 2014). This effect arises because, under sealed auctions, bidders cannot observe market signals, and thus they overbid. All of the contributions reviewed above on forest allocation problem has developed models based upon the timber auction systems actually in use. In contrast, the design of bundle-based auction system in natural resource markets has not been studied extensively.

### *2.2. Québec timber auction system*

In the previous regulatory regime in Québec, which was effective from 1987 to 2013, the government used to allocate all the volume of timber that can be harvested from public forests to sawmills through timber licences. In the new regime, the government estimates that at least 25% of the timber that can be harvested from public forests should be sold on the open market (Government of Québec, 2008). The government determines the residual needs of the mills based on the total need of the mills for roundwood (a consultation of timber licenses holders was carried out by the government to obtain information about their timber needs in the next five-year period), and the volumes that are typically consumed from other supply sources (such private forests and other provinces). The mills are then guaranteed to only obtain up to 75% of these residual needs from public forests, and the missing volumes could be obtained from public forests through auctions or procured additionally from other sources. This measure aims at ensuring that market prices can be found or estimated properly for the wood. These prices can then be used to set the prices for wood sold through timber licenses. In order to obtain the best possible and fairest prices, the TMB has to make timber available to as many buyers as possible across all regions of Québec. Mill owners, contractors, cooperatives, forestry groups and log dealers are all permitted to take part in the auctions organized by the TMB. Each year, at least three auctions must be conducted (TMB/BMMB, 2015). Information on the calls for tenders and related forest areas are made available to all parties interested on the TMB website.

Fig. 1 depicts the auctioning process. An auction starts with the posting of a public tender document (DAO) by the TMB. This document provides information about the goods offered in the bid including the volume of timber estimated by species (or groups of species), the geospatial location and the quality of timber, and the time limits. It contains also a rough description of the work related to road and harvest operations. The winner of an auction is selected based on the highest amount submitted for a bid. This amount has to be greater than the reserve price, i.e., the lowest price the TMB is willing to accept for a bid. To avoid bidders' collusion, the TMB has the authority to cancel any auction that received less than three bids. In addition, the TMB does not allow mills that belong to the same company to submit separate bids. In case of ties between two bids, the winner is determined by drawing. Afterwards, the winner has to harvest from the land assigned. The winner can also sell part of the wood harvested to another company.

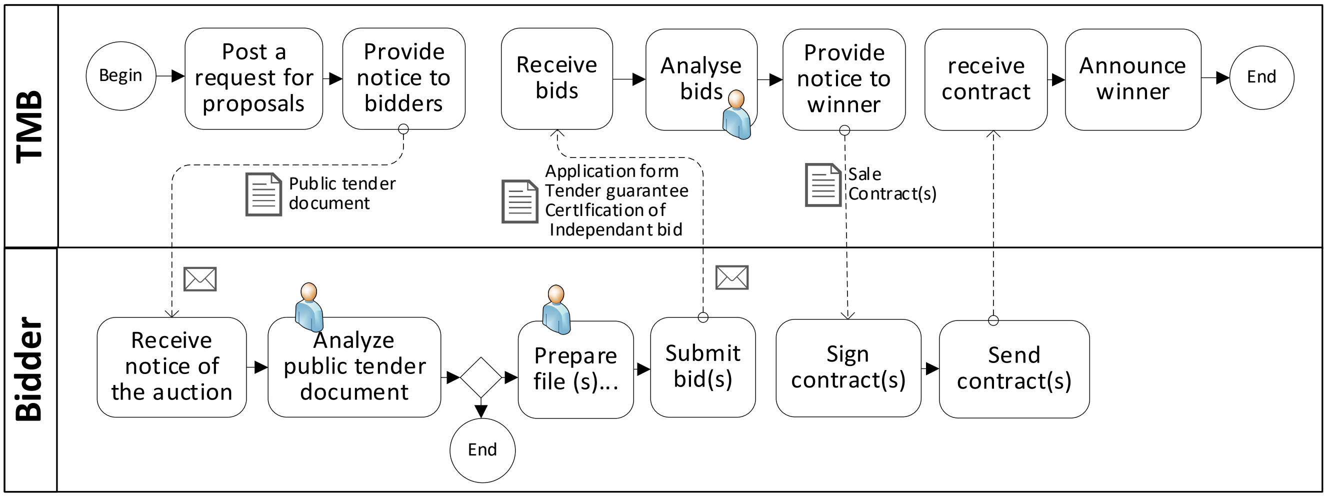



**Fig. 1** Auctioning Process currently used by the TMB (adapted from Zeidi, 2016).

During the last five years, the TMB offered 1,437 forest areas for auction, representing a total of 483,717 thousand hectares of land and near 46 million cubic meters of roundwood (see Table 1). Out of these, only 956 offers were sold, or just over the half of the lots offered each year (66% in average), thus the total auction actual sales were much less than initially expected (the achievement rate was 84% in average). In certain cases, the areas comprise some volumes that are not required to be harvested under the silviculture prescription and are added to the volume permitted, and the winner is free to harvest the additional volumes or not. Most of the offers were accepted as is, but in some cases, the TMB needed to combine certain areas that were very close to each another so that they become attractive, and the companies bid on them as single offers. This occurred particularly in the first three years. In general, the areas were sold as standing timber, which means the winners are responsible for the operations and logistics activities, which include carrying out work on forest roads, harvesting, skidding and transporting the wood. However, in a very few occasions, the TMB took responsibility for harvesting or for harvesting and delivering the timber.

Table 1 shows also that the number of winning companies keeps increasing from year to year, and some companies end up with large numbers of wins. It is clear that the costs associated with the operations and logistics activities are very high, and they become even higher if a company must relocate its equipment far away from its wood delivery terminal to distant areas or from one area to another. These costs are in fact an important reason why the companies rush to bid on the areas near their terminals or mills. The other important reason is related to the value that could be extracted from the forest areas. Indeed, forests with several tree species and age classes are typical in Québec. Therefore, each stand in the forest–a stand is a homogeneous forest area with respect to forest resources and treatments needed–has specific characteristics or can generate a set of products that are suitable for particular types of usage or industries, while it may not be appropriate for others. In other words, a part/some products of the available stands in an auction might be in the best interest of a bidder while other parts/products are not. From Fig. 2, it appears that much of the volumes offered come from the SPF species group and is mostly sold to sawmills and paper mills. The volumes offered from the other species groups are much smaller and remain mostly unsold. If we consider the all the species included in the four group for which the TMB can announce volumes for sale, and the fact the TMB tags theses volumes as ‘lumber volumes’ or ‘pulp wood volumes’, then the number of different products that can be extracted from the forest can be as high as 60 different products. The problem resides in the fact that a forest area can deliver several products simultaneously.

**Table 1**
**Summary of auction sales data in Québec for the years 2012–2017 (TMB/BMMB, 2017).**

| Characteristics | 2012-2013 | 2013-2014 | 2014-2015 | 2015-2016 | 2016-2017 |
|---|---|---|---|---|---|
| Areas & Offers (one area per offer) | | | | | |
| Total number of areas/offers | 203 | 264 | 255 | 372 | 343 |
| Total area of areas offered (ha) | 54,021 | 93,554 | 90,533 | 131,863 | 113,746 |
| Total mandated volume (Million m3) | 5,408 | 8,570 | 8,658 | 12,516 | 10,639 |
| Total optional volume (m3) | 0 | 0 | 0 | 0 | 123,570 |
| Areas sold as "Scaling standing timber" | 99 | 164 | 155 | 241 | 206 |
| Areas sold as "Scaling delivered timber" | 2 | 0 | 1 | 7 | 0 |
| Areas sold as "Inventory standing timber" | 15 | 12 | 20 | 6 | 15 |
| Areas sold as "Scaling harvested timber" | 3 | 2 | 0 | 5 | 3 |
| Areas removed | 0 | 0 | 0 | 10 | 2 |
| Offers acceptance | | | | | |
| Percentage of areas awarded (%) | 59% | 67% | 69% | 70% | 65% |
| Offers accepted "as is" | 103 | 166 | 158 | 259 | 222 |
| Offers combined and accepted | 16 | 12 | 18 | 0 | 2 |
| Offers not accepted | 84 | 78 | 76 | 93 | 116 |
| Number of cancelled sales | 0 | 4 | 0 | 1 | 1 |
| Number of cancelled contract | 0 | 4 | 3 | 9 | 0 |
| Auction sales | | | | | |
| Total auction actual sales (CND Million $) | 31,406 | 52,352 | 68,067 | 95,641 | 71,167 |
| Total auction expected sales (CND Million $) [a] | 43,689 | 65,419 | 59,338 | 57,117 | 45,422 |
| Expected sales achievement [b] | 72% | 65% | 90% | 96% | 88% |
| Winning companies | | | | | |
| Number of winners | 41 | 54 | 56 | 64 | 56 |
| Average wins per company | 2.5 | 3.0 | 2.8 | 4.0 | 4.0 |
| Maximum wins for one company | 11 | 19 | 17 | 34 | 27 |

(a) includes only the offers for which an expected sales price is provided (Note that for 20% of offers, the expected sales price could not be collected).
(b) calculated only using the data of the offers for which an expected sales price is known.

As shown in Fig. 3, only a few number of the areas offered for auction by the TMB would result in one, two or three products, and the vast majority would generate from four to 20 different products, and some areas would result in up to 37 different products. Unless new biomass-based businesses come into play, a large number of the offered areas would continue receiving zero bid. The fact that companies in general prefer not to bid on large number of areas exacerbates the situation. Many companies indeed need to win sets of stands rather than single stands in order to meet their timber needs or to increase their chances to win. However, they do not do this for fear to win more than they actually need. Unfortunately, the currently used auction system lacks the flexibility to allow bidding for several forest areas simultaneously, i.e., bidders are not allowed to create bundles of preferred forest areas and to submit a single bid price for each bundle.

It is worth mentioning that the TMB uses two kinds of auctions, namely, the single-area auction and a form of a very limited combinatorial auction. The single-area auction is a FPSB auction for one area. However, the combinatorial auctions are FPSB auctions where specifically designed bundles (usually two forest areas offered at the same time and very close to one another) are offered simultaneously. Thus, companies either are allowed to bid on single areas or on two bundled areas and only the bundles that maximize the government's revenue are accepted. In this particular context, determining the winning bids is straightforward; but it would not be if companies were allowed to decide which areas to combine in a bundle. This question is dealt with in this paper. The TMB allows separate firms to bid jointly for the right to harvest areas in forests with two or more dominant species (known as mixed-forests). While such joint-bidding might increase the allocative efficiency of the auction mechanism by allowing the allocation of each species of trees to a user who seeks it, it has some downsides. Indeed, by turning two individual bids into a single bid, joint bidding reduces competition and requires explicit agreements between bidders (Rondeau et al., 2016). Combinatorial auction, as considered in this paper, tend to resolve this kind of problems.

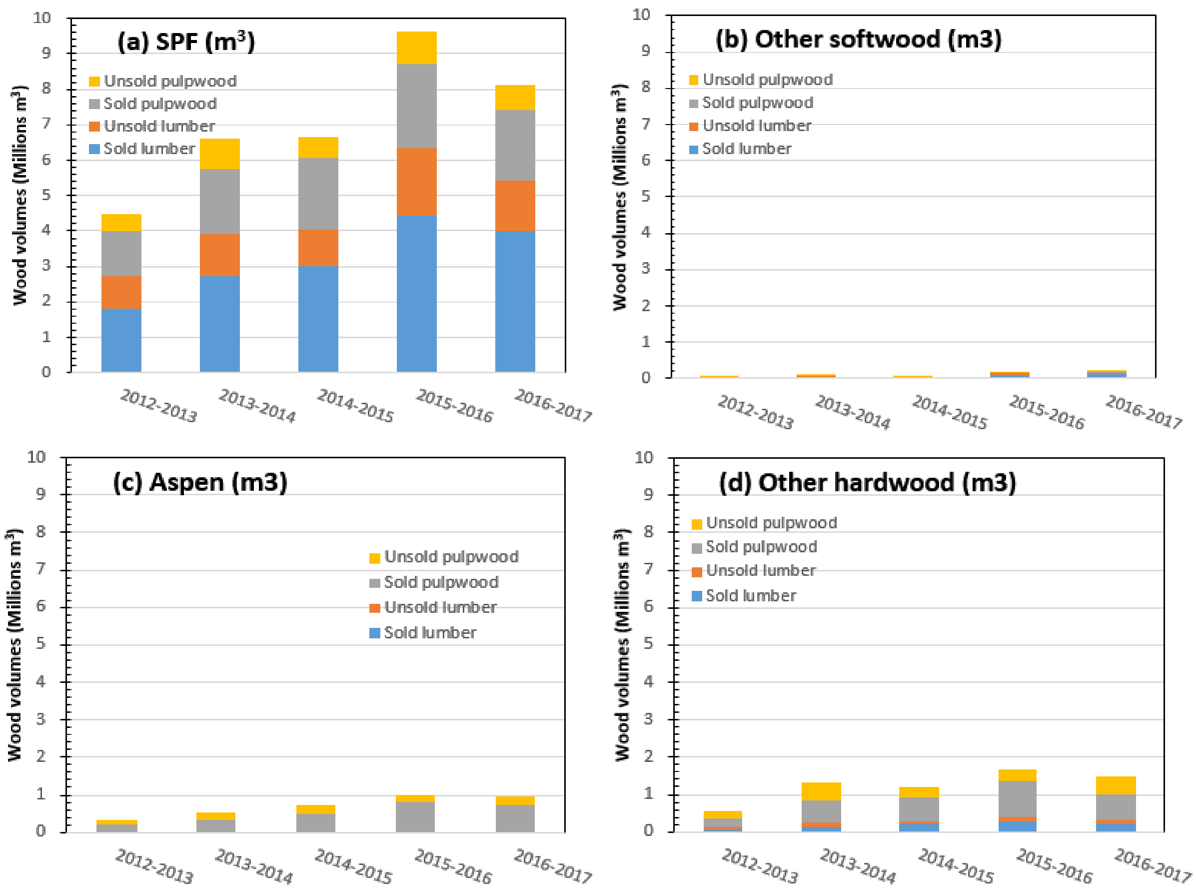



**Fig. 2.** Distribution of the sold/unsold volumes per species group. The SPF species group include spruce, fir, larch, jack pine, and other SPF. The Other softwood species group include white and red pine, hemlock, cedar, Norway spruce, and other softwood. The Other hardwood species group include sugar, red and other maple, hickory, cherry, oak, ash, white and black ash, beech, walnut, elm, ironwood, basswood, yellow and white birch, and other hardwood. Finally, the Aspen species group include poplar and balsam poplar.

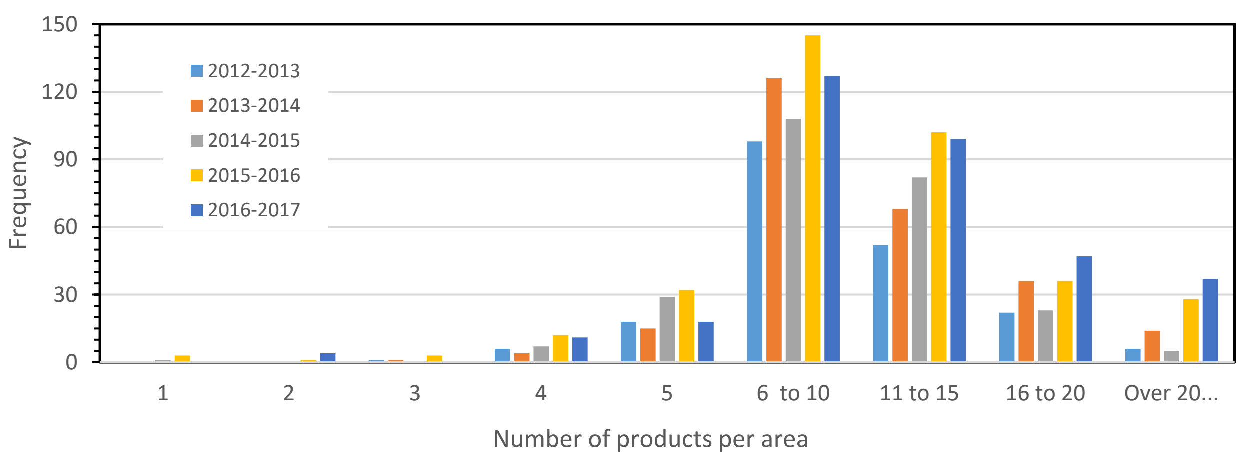



**Fig. 3.** Distribution of the number of products per area.

A crucial advantage of combinatorial auction is its tendency to assign bundles for companies best able to benefit from them, and a company with the highest interest in a bundle is likely be willing to bid higher than others are. Companies will be able to reflect on the economies of scale and logistical costs involved in different bundles. Some areas may have better species composition, and/or be closer to the bidder. In particular, closer areas will result in lower harvesting and equipment relocations costs as well as shorter transportation routes. Thus, giving companies the opportunity to submit bids in bundles could increase the number of participants in the auctions, and government revenue out of the bids will increase. As a result, the auction becomes more efficient. However, it is risky; the bidder gets either entire combination or nothing. Such auctions are also more complex. The bidder has to decide on a number of choices, such as the best collection of bundles on which bids are allowed to be restricted or not, how much price to allocate for each bundle, and so on. The problem becomes even more complex if the bids are conflicting.

## 3. Methodology

The methodology consists in assessing the performance of two combinatorial auctioning systems allowing bidders to form their own bundles under certain constraints. While the focus is on the design of the system and the winner determination problem, we propose simple heuristic strategies to solve the bid expression problems for companies. It is difficult to tell a priori which configuration is more efficient than the other as this depends significantly on the rules defined by the seller to govern these systems and on the strategies adopted by the companies to meet these rules. Thus, comparisons need to be made within the context of increasing government revenues from timber sales through auctions in Québec. To conduct these comparisons, we propose the framework depicted in Fig. 4. The four stages in this framework are context-specific, relating to the number of forest areas to be offered for auction to the number of companies that can be supplied from these areas, and the comparative scale of the volumes of supply needed by these companies. In the following subsections, we describe the system design rules, auctioning strategies, and winner determination model used respectively in stages 2, 3 and 4, and we provide an illustrative example.

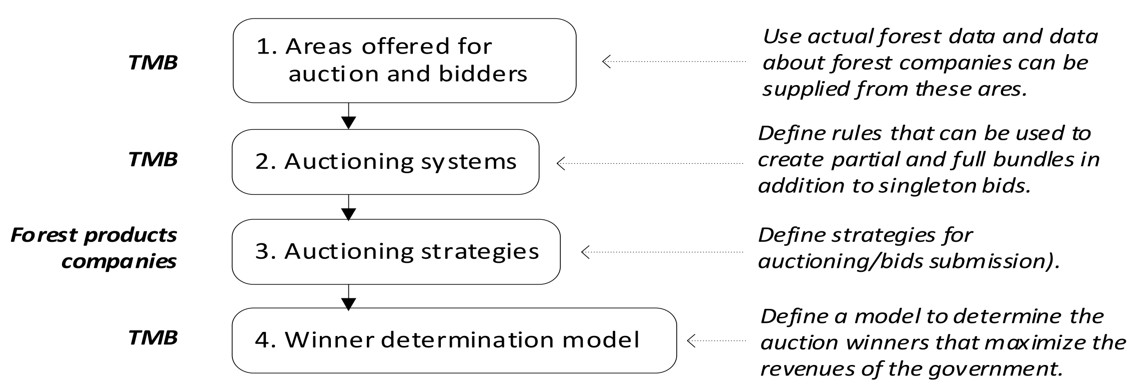



**Fig. 4.** Framework for analyzing and comparing bundle-based auctioning systems.

### 3.1. *Design of the auctioning systems*

In addition to the traditional singleton bids auctioning system, two other FPSB auctioning systems were designed where partial and full bundles of available forest areas can be formed. When full bundles need to be formed, the bidder can only bid on combinations of stands so that the total volume of the bundled stands covers the bidder's required wood supply through the auctioning system. However, when partial bundles need to be formed, several bundles of smaller volumes are allowed. The bidding rules and auctioning strategies defined in Table 2 were used. A company gives one price to a bundle at the start of the auction, and each bundle can have a different price. While none, one or many bids can be selected for each company under the singleton bids and partial bundles auctioning systems, only one bid or none can be selected for each of the participating companies under the full-bundle auctioning system. In all cases, the TMB selects the bids that maximize government revenues.

**Table 2**
**Auctioning systems and strategies.**

| Auctioning systems | Bidding rules | Auctioning strategies |
| --- | --- | --- |
| Singleton bids | Each company can submit as many bids as desired on single forest areas. | Conservative strategy<br>- Companies cannot risk winning more wood than needed.<br>- Each company bids on one or several areas in decreasing order according to the net value, up to 100% of the total volume it needs to win*. |
| | | Aggressive strategy<br>- Companies can take a low risk of not winning any wood.<br>- Each company bids on one or several areas in decreasing order according to the net value, up to 150% of the volume it needs to win*. |
| Partial bundles | Each company can submit up to 25 bids on different bundles. | - Each company forms 25 bundles, each meeting between 20% and 60% of the total volume it needs to win*.<br>- An area can only appear in up to three different bundles. |
| Full bundles | Each company can submit up to five bids on five different bundles. | - Each company forms five bundles, each meeting between 95% and 105% of the total volume it needs to win*.<br>- An area can only appear in up to three different bundles. |

**The toal volume a company needs to win through auction corresponds to 25% of its total needs.*

### 3.2. *Definition of the auctioning strategies.*

In practice, companies can adopt different strategies within the rules of the auctioning system set in place by the TMB. However, in the case study presented in the next section, the companies are assigned similar strategies for comparison purposes. Table 2 highlights the strategies that, according to some experts who are highly involved in the industry, most likely could be used by the companies under each of the auctioning systems. In general, the areas or bundles of areas are formed based on reducing logistical costs and increasing net value. In partial and full bundles, the risk of not finding effective solutions for a given company could be very high especially if this company includes one or several preferred areas in many of the bundles it proposes. Thus, there is a need to limit the number of bundles in which a given area can appear. Because the number bids is unlimited in singleton bids, then a company practicing a more disciplined recognition of the risk of winning more wood than needed, would adopt a conservative ceiling on the total volume of wood it can bid on. Nevertheless, one could easily assume that buyers are only interested to bid on the areas where it is possible to harvest and bring the wood to the mill's gate at or under a targeted supply cost.

### 3.3. *Auction winner determination model*

We propose a model that is based on the generic models formulated by Abrache et al. (2007). Consider $N$ the set of bidders and $A$ the set of forest areas to sell or allocate. Each bidder $j$ can submit a bid for a bundle $s \subseteq$ A and pay an amount $p_{j,s}$. Each bidder has a set of bundles denoted $B_j$. The set of all bundles is denoted $B$. $x_{js}$ is a decision variable that take the value of 1 if the bid submitted by bidder j for bundle s wins, 0 otherwise. The objective function (1) maximizes the revenue of the seller (the government) generated from the allocation or the selling of items to the bidders. Constraint (2) ensures that no single forest area is allocated to more than one bidder. $\delta_{is}$ is a parameter that is equal to 1 if a bundle $s$ $(s \in B)$ includes area $i$ $(i \in A)$, 0 otherwise. Constraint (3) ensures that a bidder wins either a single bundle or nothing and is only used with full bundles.

$$\boldsymbol{Maximize} \ \sum_{j\in N} \sum_{s\in B_j} p_{js} x_{js} \tag{1}$$

Subject to

$$\sum_{j\in n} \sum_{s\in B_j} \delta_{is}\, x_{js} \leq 1 \qquad \forall i \in A \tag{2}$$

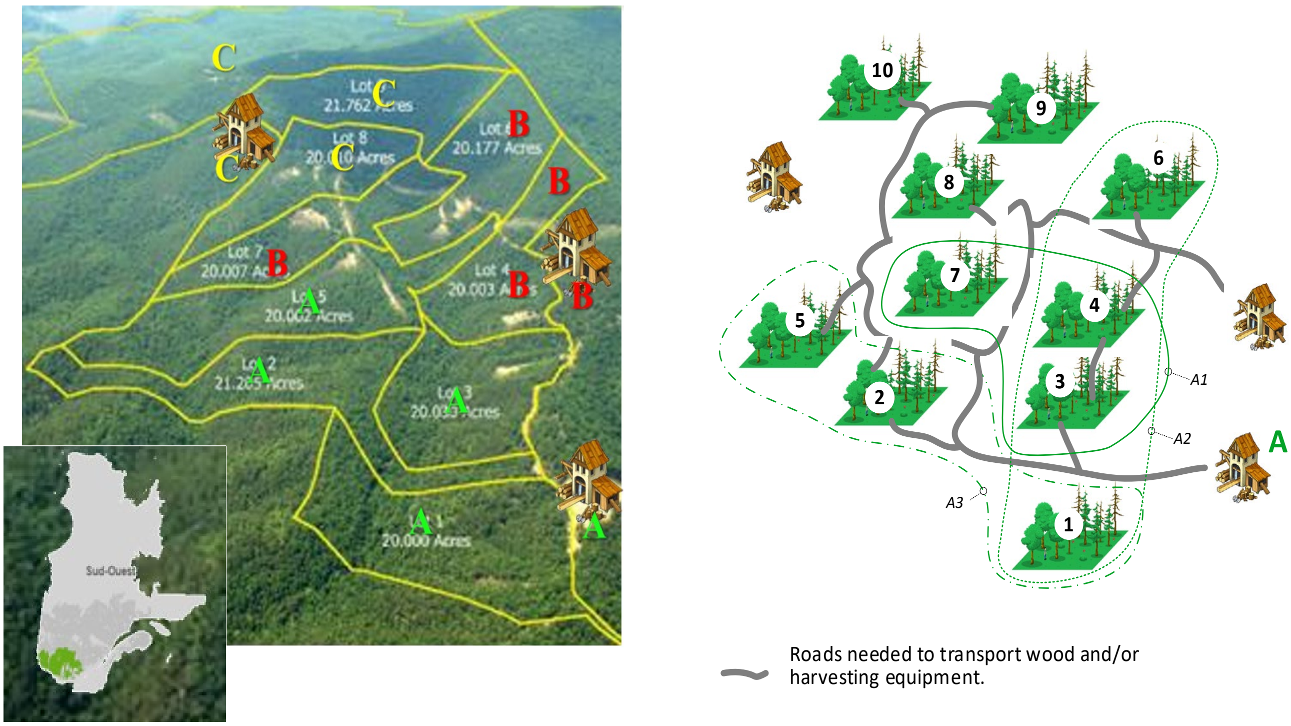
$$\sum_{s\in B_j} x_{js} \leq 1 \qquad \forall j \in N \tag{3}$$

$$x_{js} \in \{0, 1\} \qquad \forall s \in B, \quad \forall j \in N \tag{4}$$

The resulting model is a mixed-integer programming problem. Finding an optimal solution to such a model, and whereas more than one optimal solution exists, is essential. This is because a close to but not optimal solution might be a wood allocation that unfairly benefits certain companies over others. Other practical restrictions in the generation of bundles are a maximum number of bundles, the number of areas in each bundle, and limits on the overall area size given to a single bidder. Therefore, it is necessary to solve the problem using an efficient solution algorithm.

*3.4. Illustrative example*

To better understand how resorting to bundles can improve the efficiency of traditional auction systems; consider the example shown in Fig. 5. Three identical bidders in size and capacity (sawmills A, B, and C) are bidding on ten areas that have mixed species (1-10).




(a) (b)

**Fig. 5.** Example of bundle-based auction system. (a) Geospatial location of the forest areas, (b) Bundles formations for company A.

As shown on Fig. 5a, the average volume of wood needed by each sawmill is around 80000 m$^3$, and the volume of wood that can be harvested from each forest area is around 20000 m$^3$. Suppose that bidder A has interest in areas 1, 2, 3, 4 and 7 due to the species available in these lots. In the context of the current system, bidder-A has to submit bid for each area separately. Since the lot in area 7 is relatively far, transportation and logistics costs is expected to be \$ 60. Knowing that his/her break-even point is \$100, then bidder-A would submit a bid of \$40. Similarly, bidder-A will bid on lot 1. On the other hand, if the bidder submits a bundle of lots 3, 4, and 7 (bundle A1 in Fig. 5b), the costs would become \$40 and then he/she would pay \$60 for the bid. Bundle A1 lots are close to bidder A, hence paths which are required have many segments in common, i.e., less time and cost are needed to build the desired routes. Since bundle A1 does not meet the sawmill needs, then bidder A should also bid on another area, for example, area 1 or area 2. A similar observation can be made if bidder A bids on bundle A3. However, bidder A can also bid on bundle A2 because it provides the total needs and the logical costs could be very interesting especially if the road segment linking area 3 to area 4 is already in place. Similar analyses can be made for companies B and C.

From the discussion above, it is therefore conceivable that the bundling system can be one where buyers need to form full or partial bundles. In both systems, the bidder specifies a single valuation for any given bundle. A company needs to win only one auction under a full bundle auctioning system, and two or more auctions under a partial bundle auctioning system.

## 4. Case study and materials

A case study was assembled to assess the value creation potential of the two proposed combinational auction systems and provide an illustration of the benefits of bundle-based auctions for timber sales in Québec. The study area concerns the Northwestern part of Québec where, in 2015, the TMB selected 44 forest areas for sale through auctions. Fig. 6 shows the locations of these areas and the eight sawmills (indicated on the map as demand points D1 to D8) that were expected to bid on these areas with the aim to purchase on the open market at least 25% of the wood they need. Five different companies owned these eight sawmills, with three companies each with two sawmills. We assumed that the bidders do not make any assumptions about the potential number of other bidders, their identity or strategy. In addition, we assumed that each company assesses the amount that it is willing to pay for a given area by multiplying the market price of a cubic meter of wood by the estimated volume to harvest in the area, and by adding the costs incurred in harvesting this wood and delivering it to its mill(s). The cost of delivering the wood includes all the expenses related to equipment relocation, road and harvest operations, and transportation. A company might adjust the resulting amount as may be necessary if the area appears to be particularly interesting (for example, because of the tree species or the age classes). All the costs were estimated from the recent operating costs and earnings survey of the lumber and forest industry in Québec (Groupe DDM, 2016). This data is used to evaluate the auctioning systems and strategies defined in Section 3. The results are presented in the following section.

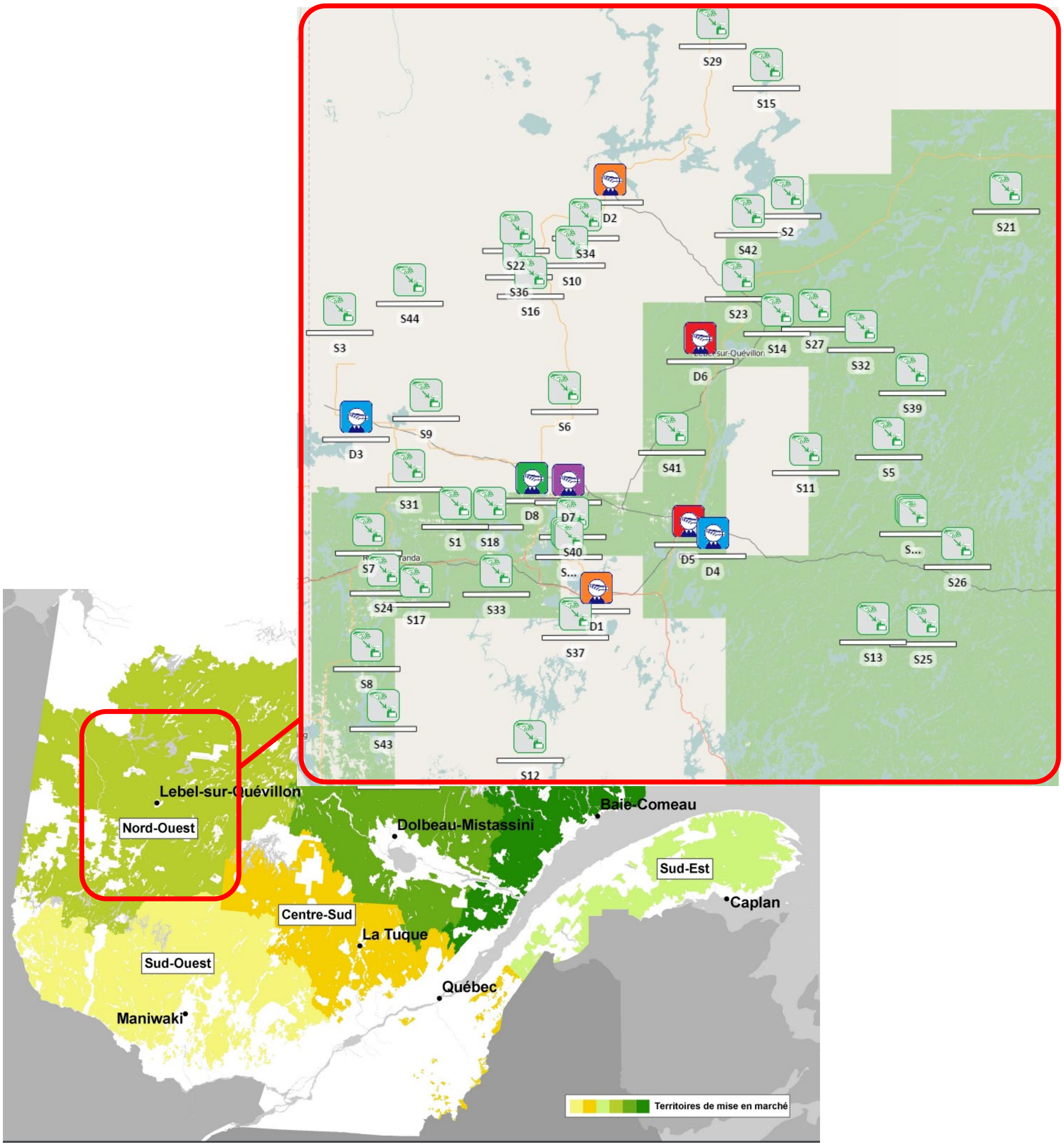


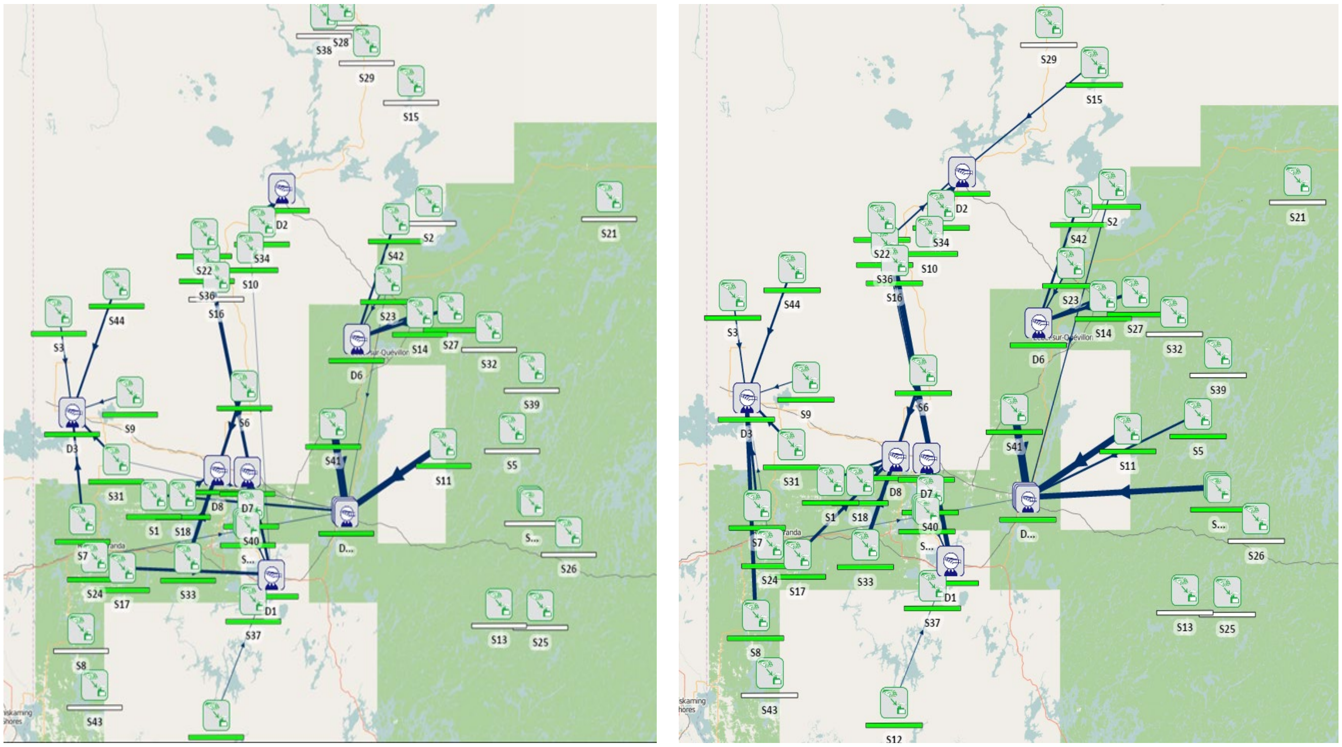

**Fig. 6.** Locations of the forest areas (S1 to S44), sawmills/demand points (D1 to D8) and companies (C1 to C5) in the northwestern region of Québec considered for the case study.

## 5. Results

We used the IBM ILOG CPLEX Optimization Studio 12.5 to solve the defined auction winner determination models. Table 3 shows the number of bids submitted and bids won, the actual wood volumes that need to purchase on the open market and the total volumes won with corresponding costs and transportation distances are indicated for each company and for the different auction systems and strategies that were tested.

Our results indicate that the requirements of the companies could not be satisfied under the singleton auctions and conservative auctioning strategy. In fact, no company could win all the wood it needs. Even worse, company C4 could hardly obtain half of its requirements and runs the risk of not being able to satisfy all its demand especially if it cannot expect to be supplied from private forests. Indeed, there are very few private forests owners selling wood in the region. Nevertheless, the TMB was able to sell 1 million $m^3$ of wood that generated slightly more than 15 million \$. As we explain below, these numbers are clearly below the figures that could be expected from an aggressive strategy or from the bundle-based auctions.

Indeed, under the singleton auctions and aggressive strategy, the government sold near 30% more wood and collected more than 53% more revenues. In fact, by applying an aggressive strategy, some companies ended up with higher wood volumes than needed. For instance, company C5 won almost all the areas it bid for. As a result, it ended up with an extra 75000 $m^3$ of wood. The company can decide to harvest this wood another year but it might want to avoid this choice as it can lead to financial (cash flow) problems. The extra 75000 $m^3$ of wood it won actually exceed the total volume needed by company C4. The latter still could not secure half of its wood requirements. In fact, under the conservative strategy, sawmill D7 did not win against sawmill D8 in the vicinity, so it could not have hoped for better as it could not bid more aggressively when the other companies were also bidding aggressively. But even though the total volume won could not be improved, company C4 need to spend more to harvest and deliver the wood to its mills, as the areas in the vicinity were won by company C5 (see Fig. 7). The lines on Fig. 7 indicate wood flows; the thicker the line, the higher is the flow. In certain cases, the flows are crossing when the areas won are located very far from the mills. This is particularly the case when the companies bid aggressively.




(a) (b)

**Fig. 7** Locations of the areas allocated to the mills in the singleton auctions. (a) Conservative strategy, (b) Aggressive strategy.

With the bundle-based auctions, the resulting winner determination problem is in general solved in less than a minute of computing time on an IBM (8 GB RAM, 2.3 GHz processor) laptop computer. The results show that the government made higher revenues than the conservative strategy but not as high as with the aggressive strategy of the singleton auctions. Nevertheless, the companies were in general successful in obtaining wood volumes of the same order as their requirements at lower expenses. Company C5, for instance, won almost all the volume it needed but the expenses were more than 10% lower. Company C4 made progress in obtaining more volume and the expenses were particularly lower. This could be explained by the fact the sawmills were not too distant from each other, and the fact the bundles were in general formed on a geographical basis, that is, whenever possible, areas that are close to one another are included in the same bundle so as to minimize logistics and harvesting costs. In addition, because the sizes of the companies remain comparable, it can be inferred that chances that one company or another wins a specific bundle are reasonably comparable. In other words, the difference in the auctioned prices could be insignificant.

**Table 3**
**Number of bids, wins, total volumes and costs for the different auction systems and strategies**

| Company | No. of mills | No. of bids submitted | No. of bids won | Total wood requirement ($m^3$) | Total wood won ($m^3$) | Requirement satisfaction (%) | Expenses ($\$/m^3$) | Distance to area(s) (km) |
|---|---|---|---|---|---|---|---|---|
| Singleton auctions with conservative strategy | | | | | | | | |
| C1 | 2 | 13 | 8 | 278100 | 254700 | 91.6 | 14.54 | 104.7 |
| C2 | 2 | 18 | 8 | 302725 | 275500 | 91.0 | 13.89 | 196.9 |
| C3 | 2 | 9 | 5 | 341500 | 258300 | 75.6 | 14.48 | 79.9 |
| C4 | 1 | 7 | 2 | 150775 | 73100 | 48.5 | 20.16 | 60.0 |
| C5 | 1 | 6 | 3 | 146300 | 143950 | 98.4 | 16.55 | 86.4 |
| | Total: | 53 | 26 | | Average: | 81.1 | 15.93 | 105.6 |
| Singleton auctions with aggressive strategy | | | | | | | | |
| C1 | 2 | 19 | 9 | 278100 | 305750 | 109.9 | 19.06 | 173.6 |
| C2 | 2 | 22 | 10 | 302725 | 420000 | 138.7 | 14.36 | 146.6 |
| C3 | 2 | 14 | 6 | 341500 | 279050 | 81.7 | 18.62 | 64.3 |
| C4 | 1 | 9 | 2 | 150775 | 73100 | 48.5 | 23.91 | 60.0 |
| C5 | 1 | 11 | 5 | 146300 | 221300 | 151.3 | 18.89 | 78.8 |
| | Total: | 53 | 32 | | Average: | 106.1 | 18.97 | 104.7 |
| Partial-bundles auctions | | | | | | | | |
| C1 | 2 | 25 | 4 | 278100 | 282400 | 101.5 | 18.18 | 86.4 |
| C2 | 2 | 25 | 3 | 302725 | 288500 | 95.3 | 17.94 | 118.3 |
| C3 | 2 | 25 | 3 | 341500 | 352000 | 103.1 | 15.71 | 143.1 |
| C4 | 1 | 25 | 2 | 150775 | 125400 | 83.2 | 13.36 | 94.5 |
| C5 | 1 | 25 | 3 | 146300 | 147050 | 100.5 | 14.84 | 152.6 |
| | Total: | 125 | 15 | | Average: | 96.7 | 16.01 | 119.0 |
| Full-bundles auctions | | | | | | | | |
| C1 | 2 | 5 | 1 | 278100 | 287100 | 103.2 | 19.73 | 70.3 |
| C2 | 2 | 5 | 1 | 302725 | 310800 | 102.7 | 18.80 | 107.1 |
| C3 | 2 | 5 | 1 | 341500 | 341000 | 99.9 | 15.75 | 135.5 |
| C4 | 1 | 5 | 1 | 150775 | 158250 | 105.0 | 13.68 | 101.3 |
| C5 | 1 | 5 | 1 | 146300 | 147050 | 100.5 | 14.84 | 152.6 |
| | Total: | 25 | 5 | | Average: | 102.3 | 16.56 | 113.4 |

In order to understand the impact of the bundle formations on the chances of the companies to obtain the volumes they needed, we conducted a sensitivity analysis. First, we compiled all the forest areas that were selected by the TMB for sale through auctions in the region in 2014, 2015 and 2016. This resulted in a set of 139 areas. Then, we replicated our simulation experiments 30 times. In each replication, we used a different set of 44 areas drawn from a set of 139 areas. Table 4 show that the companies tend to receive all the wood they need when the auctioning system is based on partial-bundles. However, when the auctioning system is based on full-bundles, the companies run a quite significant risk to receive no or a small volume of wood. This risk is particularly high for company C4. It is true that company C4 is much smaller than the other companies and its single sawmill is located near other sawmills. However, the fact that the number of bundles that the company can form is limited to five may have prevented the solver from finding a better solution to this set partitioning problem.

**Table 4**
**Analysis of the robustness of the bundle-based anctioning systems**

| Company | No. of mills | No. of experience where some volume is granted | No. of experience where no volume is granted | Requirement average satisfaction (%) |
|---|---|---|---|---|
| Partial-bundles auctions | | | | |
| C1 | 2 | 30 | 0 | 101.0 |
| C2 | 2 | 30 | 0 | 104.2 |
| C3 | 2 | 30 | 0 | 103.6 |
| C4 | 1 | 29 | 1 | 101.4 |
| C5 | 1 | 29 | 1 | 97.5 |
| Full-bundles auctions | | | | |
| C1 | 2 | 30 | 0 | 101.0 |
| C2 | 2 | 29 | 1 | 99.4 |
| C3 | 2 | 26 | 4 | 86.3 |
| C4 | 1 | 21 | 9 | 56.0 |
| C5 | 1 | 28 | 2 | 96.6 |

Table 4 presents the number of experiences where each company won or did not win some auctions (that is, all or some volume is granted, or no volume is granted) as well as the average requirement satisfaction throughout the 30 replications. The companies tend to receive all the wood they need when the auctioning system is based on partial-bundles. However, when the auctioning system is based on full-bundles, the companies run a quite significant risk to receive no or a small volume of wood. This risk is particularly high for company C4. It is true that company C4 is much smaller than the other companies and its single sawmill is located near other sawmills. However, the fact that the number of bundles that the company can form is limited to five may have prevented the solver from finding a better solution to this set partitioning problem.

## 6. Conclusions

Current timber auction system in Québec needs to be improved in order to better incorporate the bidders' interest and preference. In this paper, we analyse the effectiveness of different bundling systems in maximizing government revenues and enhancing bidders competitively. Our results show that the use of the option of bundling forests areas makes the auction process more beneficial to the majority of stakeholders. Government revenues are increased, the bidding companies are more likely to obtain the desired volumes and pay less for harvesting and equipment relocation, and greenhouse gas emissions are reduced. The "all-or-nothing" basis of the full-bundles auctions remains however a source of risk for the companies, as the volumes considered in this study accounts for 25% of the mills' total supply.

This research presents an investigation of simple bid expression and bundle generation strategies in a specific forest region. The nature of the investigation has important limitations. First, in order to reduce the risk of not being able to form effective bundles for any given company, we limited the number of bundles in which a given area can appear to three different bundles. We acknowledge the fact that additional experiments performed in other regions of Québec could lead to a different context-specific assessment of the potential of the bundle-based combinatorial auction systems proposed in this paper. Moreover, two research avenues can be identified to further develop these systems. Firstly, the bid expression strategies used in the studies are simple and heuristic in nature. Further improvements in wood sales or reductions in sawmills' harvesting and logistics costs may be achieved by considering more advanced bid expression and bundle generation strategies. Mixed-integer programming models could be proposed for such problems. Secondly, we believe that considering additional types of bidders besides the main consumers (sawmills) would lead to a richer understanding of the problem.

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