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Time-Based Combinatorial Auction for Timber Allocation and Delivery Coordination

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Abstract:

The timber auction system currently used in the province of Québec, Canada, is a single unit auction, in which timber users bid on entire forest stands located within a specific area. In this procurement system, timber users (i.e., winners) are responsible for harvesting the entire stands and for reselling undesirable timber species to others. In order to improve the limits of this system, this paper proposes a sustainable auction system, referred to as time-based timber combinatorial auction. In this approach, time is not part of the definition of the goods for sale. It is used to valuate the good for sale with respect to their expected delivery period. Therefore, this system aims to simultaneously allocate multiple goods, or products in mixed forest stand, to multiple winners, and address the coordination of timber deliveries to their winners. The proposed timber combinatorial auction provides an open access allocation of timber, based on its intrinsic economic value, while allowing the Ministry of natural resources to exercise high standard for environmentally friendly forest operations. From a logistic point of view, a sensitive analysis is conducted in order to compare the proposed time-based combinatorial auction with a combinatorial auction with no delivery coordination. Both models are compared according to bidders' and seller's time flexibility. Experimental results illustrate the impact (i.e., cost) of delivery coordination on total revenue due to loss of value when time preference is not fully satisfied. This cost evaluation can then be used as an upper bound of the cost of coordination, when delivery coordination must be manually negotiated among multi-stakeholder.

Keywords: combinatorial auction, timber auction, coordination, wood freshness, winner determination problem.

1 Introduction

Former Québec forest regime, which was based on an exclusive long-term licencing system, was unable to establish a fair price for timber transactions, and therefore a sustainable economic system. Consequently, under the pressure of international trade agreements, the Québec government, along with others provinces in Canada (Niquidet and van Kooten, 2006), decided to make a portion of the annual timber supply (25%) available to anyone through an auction system. With timber available through auctions, buyers can access a larger timber supply according to the value of their own forest products market. In such a context, designing an efficient auction system while preserving a certain level of guaranteed supplies for Québec companies can become a complex task. Different goals are pursued such as offering a certain level of stability to traditional users, offering opportunities to new entrepreneurs and assuring a fair financial return for the public asset. In order to do that, the government currently uses an auction system in which entire forest stands are sold to a single winner. The advantage of this type of auction is that it is rather simple to implement. Bidders can assess the volume of each species available in each stand for sale and evaluate their worth, whether the stumpage sale is lump-sum sale (i.e., one price for the entire stand) or a scale sale (i.e., a unit price -per foot, board measure (fbm), cord, post, etc.- for each species of extracted wood). Furthermore, the seller is not involved in a complex winner determination problem.

Timber procurement planning in public land and in a multi-firm setting involves many issues that must be considered simultaneously. First, the sharing of the available volumes among forest companies must consider the specific needs of each forest companies, the scheduling and coordination of harvest and delivery activities, wood freshness, as well as the transaction prices for procurement services. When an auction process is introduced in such a context, as it is being introduced in the province of Québec, timber procurement becomes more complicated, which, in turn, forces forest companies to adapt to the new procurement environment.

In the context of public land, timber procurement planning is generally a multi-firm decision problem, which requires the coordination of several companies. Coordination is defined as the management of interdependencies among distinct activities (Malone and Crowston, 1994). In the context of supply chain management, because companies are self-interested, the coordination of their activities with others is essential to improve supply chain efficiency. In the context of timber procurement in public land, such coordination involves several aspects to address, including (1) input-output coordination in time (i.e., what and when), since the forest companies that are responsible for forest operations, harvest entire mixed forest area and deliver uninteresting species/qualities to other companies; (2) quantity availability (i.e., how much), which is a global constraint for all potential timber user; (3) self-interested forest companies (i.e., simultaneous competition and cooperation), which implies that they are responsible for managing their own procurement process, for competing with others, as well as for cooperating with others to coordinate their operations.

In a multi-firm context, timber procurement planners face several challenges. As mentioned above, one of these challenges is associated with the coordination of the distribution of volumes among buyers. The allocation agreement between them should consequently consider the transaction prices (i.e., stumpage sale prices), the timing of the procurement activities, and the wood freshness. Therefore, the coordination of forest operations and the scheduling of deliveries are crucial activities, because timber deterioration and wood freshness influence timber value. In other words, timber procurement planners must coordinate their operations with other companies, which are also involved in planning their own procurement and for meeting their own objectives.

Timber procurement planning and coordination involves a multitude of internal and external factors. In a mixed forest public land environment, forest companies may supply each other through their forest operations. In order to address part of this problem, Beaudoin *et al*. (2010) propose a timber procurement planning model in a two-firm environment based on a negotiation process. However, in the context of n forest companies (n>2), the coordination problem is more challenging and the negotiation process is more complicated. When many potential buyers are involved, auction is an efficient and practical process to allocate goods to buyers according to market value. It has therefore been used for centuries (Marty and Préget, 2010), and generally in its simplest form (i.e., first-price sealed-bid auction, Brown *et al*., 2012), for the allocation of pure or mixed species forest stands to forest product companies. Although such market mechanisms, when used in conjunction with government control mechanisms, are instrumental to the creation of a sustainable forest management approach (Kant, 2010), these rather simple applications of the single unit first-price auction cannot directly address the multi-firm coordination problem of forest operations. In Québec, this coordination problem is left to forest companies, which are ultimately responsible for managing their own forest operations within a specific period of time (from months to years) and for reselling undesirable species/qualities to other companies or users. Because mixed species forest stands can be considered as not just one but several goods for sale (i.e., combinations of species/quality), combinatorial timber auction can solve simultaneously the allocation of available wood to potential users and the coordination of harvest and delivery operations.

In combinatorial auctions, a variety of different goods are available in the market. Combinatorial auctions are particularly appropriate when bidders' valuation process depends on the set of goods they wish to purchase. In this paper, we propose a novel application of the combinatorial auction in order to simultaneously allocate the available volumes of mixed species stands to multiple users, and to coordinate timber deliveries and, indirectly, forest operations. To achieve these goals, the proposed combinatorial auction model first allows bidders to bid not only on entire stands (as in traditional first-price auction systems), but also on any combination of species/quality present in these stands. This type of auction helps bidders to directly meet their needs by bidding on the portions of the stands that matches their requirements. This auction system would also stop "bid skewing" behaviours, as described by Athey and Levin (2001), that occurs when bidders take advantage of estimation error of volume availability (made by the seller) in order to create winning bids that generate lower post-harvest cost.

Next, the proposed combinatorial auction system allows bidders to express different values for these combinations of species/quality according to their delivery period. In other words, timber is sold delivered to the mill, which requires the seller to coordinate in time the deliveries of multiple species/quality combinations to multiple buyers. This paper thus proposes a novel Winner Determination Problem (WDP) model capable of simultaneously allocating timber to mills and coordinating their deliveries to multiple buyers. This auction model is more complicated to implement and operate for both the auctioneer and the buyers. However, it is also interesting for smaller forest product companies that want to participate in the auction, but have little bargaining power to coordinate the delivery of their portion of the stand with larger companies. This may, in turn, encourage participation in the auction.

The paper is organized as follows. Section 2 explains the theoretical background of the related auction model. The time-based combinatorial auction model is introduced in Section 3. In Section 4, the winner determination problem model of the proposed auction system is discussed along with its solution limitations. The experiments including the comparison of time-based combinatorial auction and regular combinatorial auction is presented in Section 5. Section 6 presents and analyzes the results of the comparison of the two auction models, including the sensitive analysis of different factors. Finally, Section 7 concludes and discusses the limitation of the time-based combinatorial auction.

2 Theoretical background

Allocating and valuing natural resources such as timber stumpage, oil, mineral rights, and bandwidth spectrum are fundamental problems in the modern economy. Many types of auction models have been used to solve timber allocation problems and to ensure an accurate market price (Mead (1967), Hansen (1985), Paarsch (1991), Elyakime *et al*. (1994, 1997), Baldwin *et al.* (1997), Haile (2001), Athey *et al.* (2011)). Farnia *et al*. (2013) simulated and designed an approach for multiple-round timber Auction. Different bidding strategies were simulated and compared in various auction setup configurations. The authors suggest specific parameter configurations in order to maximize the seller's revenue, including the number of auctions per year, the lot size, as well as the auction periodicity. However, like the auction model used in practice, these contributions generally consider single unit (i.e., entire forest stand) auctions for timber allocation, rather than combinatorial auctions, in which each species of a single forest stand can be sold separately.

In a combinatorial auction, as described by Cramton *et al*. (2006), several items are for sale, and bidders can make offers on any sub-set of these items. The winners are the combination of offers that maximize the combined value of these offers. In order to solve these problems, Sakurai *et al.,* (2000) present an algorithm to determine the winners in complex auction setups, such as Internet auction. Bai and Zhang, (2005) consider the reserve price in the context of multi-unit combinatorial auction and presented a new algorithm to solve the WDP. Some researchers consider other attributes as well and propose a solution to combine these attributes with existing WDP models (Cantillon and Pesendorfer, 2007).

In the basic combinatorial auction models, the items for sale are single units that can only be sold entirely. However, items can also be multiple indistinguishable units, which can be sold to multiple bidders. This auction model is referred to as the multi-unit combinatorial auction (MUCA). Similarly, Rabotyagov *et al*. (2013) present a multi-unit market mechanism for forest services. The results showed that fewer bids are more likely to result in higher sale price.

Resource allocation in time and scheduling problems are another type of applications of combinatorial auctions. Several studies have been conducted on this topic in the literature. For instance, Rassenti *et al*. (1982) proposed a combinatorial auction approach to allocate airport landing time slots to competing airlines. Along the same line, Ghassemi Tari and Alaei (2013) proposed a combinatorial auction system for allocating and scheduling TV commercials. Similarly, Wang and Dargahi (2013) propose another approach of combinatorial auction application to constrained manufacturing capacity allocation in the context of mass customization.

Combinatorial auctions are also used in many decentralized and agent-based scheduling problems (De Vries and Vohra, 2003; Cramton *et al.*, 2006; Brewer, 1999). Wellman *et al.* (2001) developed a distributed bidding protocol based on combinatorial and ascending auctions to propose a solution to a complex scheduling problem. Similarly, Jung and Kim (2006) investigated the load-scheduling problem of several cranes in maritime container terminals. In the same vein, Lau *et al.* (2007) proposed a multi-period combinatorial auction for solving a large-scale scheduling problem, in which each agent offers a determined list of jobs. Wang *et al*. (2009) present a formulation of the WDP in the context of an auction-based scheduling problem, in which time is not discretized. Instead, bids for the processing of a set of jobs are formalized using a requirement-based bidding language, which allow software agents to model specific scheduling constraints. A depth-first branch and bound search is used to solve the WDP. Similarly, Kutanoglu and Wu (1999) provide an autonomous distributed scheduling system based combinatorial auction. Other applications propose iterative combinatorial auction mechanisms in the context of agent-based scheduling. Iterative combinatorial mechanism is used when bidders cannot decide on their valuations (Parkes and Ungar, 2000; Parkes, 2001), which is not the case in this paper. In these contributions, time is generally directly part of the definition of some constraints in the winner determination problem, if not directly part of the good for sale definition. The next section compares more specifically time modeling in some of these contributions and the approach presented in this paper.

There are also other auction models, beside combinatorial auctions, which consider multiple attributes (Bichler *et al.* 1999; Suyama and Yokoo, 2005) and scoring functions (Müller *et al.* 2007; Asker and Cantillon, 2008). For example, Müller *et al.* (2007) compared combinatorial scoring auctions with combinatorial price-only auctions (i.e., regular combinatorial auction). These kinds of auctions also measure quality in addition to the bidders' valuations. In these types of auction, the seller calculates the final valuation of the products regardless of the initial valuations of participants. In other words, the calculation of the bids depends on the scores that are measured by the use of a rule or function. These scores are not necessarily equal to bidders' valuations. In this paper, although the auctioneer does not use scoring rules, bidders are allowed to express several valuations of any sub-set of items based on the delivery period.

3 Time-based combinatorial auction

This section presents an extension of the classical combinatorial auction model, which aims at simultaneously allocating each individual timber product in a mix species forest stand, and coordinating harvest operations with the winning bidders preferences. The characteristics of the model are explained, including the general model description, the bid structure, as well as the winner determination problem formulation.

3.1 Auction system description

The proposed auction model is a seal-bid combinatorial auction. It is an extension of the auction model used by the *Bureau de mise en marché des bois* of the Québec government, which only sells entire forest stands of various sizes. In this model, we make a number of assumptions.

First, the forest stands for sale are mixed, which implies that they contain different species and quality of timber. This assumption is particularly true in Canadian natural boreal forest. Second, there are several kinds of bidders. It assumed that bidders could be loggers and entrepreneurs, who do not directly transform timber as they only harvest and resale timber to different customers. Bidders can also be small or large forest product companies from different sectors (e.g., sawing, pulp and paper, cabinet, wood floor, furniture, engineered wood product) that transform timber of various types into different products.

The practical consequence of such a diverse market is that each bidder may be interested in only part of a stand instead of the entire stand. Our combinatorial model therefore allows bidders to bid not only on entire forest stands, but also on any subset of products (i.e., mix of species and quality) of these stands. Consequently, because each product is sold individually, a combinatorial auction model allows the auctioneer to allocate separately each product in order to maximize revenue. However, bidders cannot bid on part of a product (i.e., a portion of the available volume of a product). Their bids must cover all or nothing of the products available for sale in the stand. For instance, a bidder may want to make an offer for all the available volume of all quality levels of a specific species. In practice, this is not a problem for bidders as volumes available are smaller than their transformation capacity. Furthermore, logs can be stored for a while, before they deteriorate. Consequently, the implementation of such an auction model could lead to many winners with complementary bids in each stand for sale.

This straightforward application of combinatorial auction already allows the auctioneer to gain control of all aspects of the sales (i.e., timber allocation). Indeed, in the auction model currently used in Québec, timber in mixed stands is allocated to winners through lump-sum sales of the entire volume of all the products available in the stand. Winners hence control the resale of undesirable products to other companies or users. In the combinatorial auction, however, the complete control of the sales also comes with the responsibility for managing forest operations and the delivery of each product to their winner. This could eventually lead to timber deterioration problems if stands are harvested too early with respect to their delivery date. Consequently, the auctioneer must guarantee an acceptable level of freshness and manage harvest and delivery operations so as to ensure that freshness meets expected level.

In order to address this issue, our timber combinatorial auction model proposes to further sub-divide the notion of combinations of product in order to add the notion of delivery time preference. In other words, bidders simultaneously bid on both combinations of products and preferred (i.e., latest) delivery period. This implies that, for any bidder, each possible combination of products can be valued differently according to the preferred delivery period. This model is referred to as a time-based combinatorial auction model.

As mentioned above, time dependent combinatorial auction is not new. However, time in the present problem does not have the same conceptual meaning as in other combinatorial auction applications of scheduling and resources allocation in time. For instance, in the application of combinatorial auction to allocate airport landing time slots of Rassenti *et al*. (1982), time compatibility is managed directly with distinct slot definitions (i.e, good for sale) and bid contingency rules. In other words, as illustrated in **Error! Reference source not found.**, all time slots are distinct goods, defined as time period usage of specific resources that are sold separately. This is not the case in our problem because the available timber is sold once. In other words, in our problem, time is only a dimension of good valuation as timber deteriorates with time. Time is therefore a characteristic of the transaction, not an attribute of the good for sale (or the good itself), as presented in **Error! Reference source not found.**. In Figure 1, the seller does not allow the bidder to offer a value for a good for every period of time, while in Figure 2, the bidders can make an offer for each good and each period of time.

The application of combinatorial auction for the allocation and scheduling of TV commercials of Ghassemi Tari and Alaei (2013), models time for each specific commercial break as a bulk product for sale. Only the upper bound of the available amount of time is thus a relevant constraint for the auctioneer. This is conceptually equivalent to the multi-unit auction introduced earlier. Once again, this is not the case in the timber allocation problem because time is not the product for sale. In the timber allocation problem, the combination of winning offers must satisfy a time constraint within which all products must be delivered in order to achieve a certain level of freshness. Indeed, in existing timber auction models, such as single unit and combinatorial auctions, there are unaddressed issues concerning timber freshness. For example, in single unit auction, because the entire lot is assigned to one bidder, the bidder must sell (in the context of mixed forest lots) the species/qualities he does not want. Because this may take time, the wood may not be fresh and may lose its quality at the time of processing. Similarly, in combinatorial auction, after winners have been announced, they must somehow agree on the specific time of harvesting of the lot. However, they may not need the items at the same time, and some of them may wish to keep their share in inventory until they need them. This coordination issue may also affect quality as harvested timber losses its freshness as time passes.

In the proposed model, because bidders announce their time preference with respect to timber delivery, the winner determination problem can directly tackle this coordination issue, and shorten the time between mixed species stand harvesting and timber processing in the mill. Therefore, although bidders may behave irrationally, they must address the need to express their delivery time preferences in the proposed bid structure. The next section describes the proposed bid structure.

3.2 Bids structure

Bids are structured as sets of triplets (product combination; period; value), as exemplified in **Error! Reference source not found.** and **Error! Reference source not found.**. In other words, each bid represents a set of valuation for each possible combination of products and delivery period (many of them being possibly void). In this example in **Error! Reference source not found.**, the bidder valuation of products $A \cup B$ is, respectively, 7, 8 and 6 for period 1,2 and 3. This bid also expresses the willingness of the bidder to buy only A for a value of 3 and a delivery in period 3, and product B for a value of 4 and a delivery in period 1. Among the 5 distinct offers contained in this bid, only one can win the auction. Therefore the bidder totally present five distinct offers which includes three offers for products $A \cup B$ in different periods, one offer for product A at period 3, and one offer for product B at period 1. These offers can be seen at the matrix in Figure 3 as non-zero elements. In this bid structure, note that the proposed timber values include all harvest and delivery costs.

Although this bid structure is more complex to manage for potential buyers, its complexity mainly depends upon the time granularity imposed by the auctioneer. Because this auction process is linked to the annual procurement planning of forest product companies (see Beaudoin *et al.*, 2007, for a description of this planning problem), it is however unnecessary to have a time-granularity that is smaller than a month. Consequently, because forest product manufacturing plants require specific mix of species and quality, forest engineers and procurement planners only need to focus on the valuation of these combinations with respect to the delivery period. Furthermore, because the Québec timber licencing system requires licensees to send annual procurement plan to the Québec government, it is natural for licensed forest product companies (which potentially represent most bidders) to use a similar time discretization in the auction system, for the purpose of integrating both business processes.

The auctioneer also has the option to use larger time periods, such as the season (3-month period length). This option allows the auctioneer greater time flexibility to plan for harvest and delivery operations, and potentially increase revenue but it is less accurate for buying companies, which are used to monthly plans. This time sensitivity is specifically studied in the experiments section.

Finally, because products are sold separately, the auctioneer (i.e., the Ministry of natural resources) has the opportunity to control specific aspects of the auction to improve fairness. For instance, large forest product companies are generally interested in a few products. During a combinatorial auction of several products from the same area, these large companies might make a global offer to make sure they obtain the products they need, while controlling both the delivery and the resale of the uninteresting products (which is also true for a simple auction). This type of behaviour would limit the ability of smaller timber users to take part in the auction, which would then be dominated by larger companies. Limiting the capacity to make offers only to specific products according to the need of the plants would therefore allow smaller timber users to participate in the auction and have a better control over timber deliveries. The next section describes the corresponding winner determination problem model (i.e., WDP).

4 Winner Determination Problem

The process of finding the winners in single unit auctions is straightforward. When the auction is combinatorial, however, a mathematical model must be designed and solved in order to find the combination of offers that maximizes revenue. As mentioned earlier, determining the winners in timber combinatorial auction requires addressing the problem of timber deterioration in time. Because wood tends to deteriorate (e.g., discoloration, decay) once trees are felled, it is necessary to deliver and process them within a reasonable amount of time, before it deteriorates. In this paper, the period length during which all deliveries must be made is referred to the delivery horizon. Therefore, the design of the winner determination problem must address specifically this type of constraints.

In general, the modeling of a winner determination problem depends directly on the auction design, the configuration of the products for sale, as well as on other specific constraints. Because our auction system has a time dependent bid structure, the WDP must include specific constraints to tackle the coordination of deliveries as well as the management of timber deterioration. The next section introduces the proposed mathematical model.

4.1 Mathematical model:

The mathematical model presented below is an extension of the WDP for regular combinatorial auctions (Shoham and Leyton-Brown, 2009). We first present the definition of indexes, sets, parameters, and variables. Then, the objective function and the constraints are presented.

Indexes and sets:

$i \in N$	set of bidders
$j \in G$	set of products
$S \subseteq G$	set of bundles of products (power set of products)
$t \in T$	set of time periods
$dt \in T$	set of dates of time periods

Parameters:

$V_i(s,t)$	agent *i*'s valuation of bundle *s* at time *t*
$Q(s)$	volume of bundle *s*
$Q(j)$	volume of products *j*
K	length of the delivery horizon (maximum allowable duration between all winning deliveries)

Variables:

$x_{s,i,t}$	Boolean variables, indicating whether bundle s is

allocated to agent *i* at time *t*

Objective function:

Maximize

$$\sum_{i\in N}\sum_{s\in S}\sum_{t\in T} V_i(s,t)x_{s,i,t} \pm \varepsilon \sum_{j} Q(j) \tag{1}$$

s.t.

$$\sum_{j\in S}\sum_{i\in N}\sum_{t\in T} x_{s,i,t} \leq 1 \quad \forall\, j \in G \tag{2}$$

$$\sum_{s\subseteq S}\sum_{t\in T} x_{s,i,t} \leq 1 \quad \forall\, i \in N \tag{3}$$

$$\sum_{s\in S}(2 * dt_1 - K)x_{s,i_1,t_1} + \sum_{s\in S}(dt_1 - dt_2)x_{s,i_2,t_2} \leq 2 * dt_1 \;\; \forall\, (i_1,t_1),(i_2,t_2) \tag{4}$$

$$x_{s,i,t} = \{0,1\} \quad \forall \;\; s \in S, i \in N, t \in T \tag{5}$$

In this integer programming formulation, the objective function (Equation 1) states that the seller aims to maximize the sum of the agents' announced valuations of the combination of products and time period (i.e., maximize revenue). The ε term is introduced in order to avoid multiple solutions for winning determination problem. Therefore, by adding ε and multiplying it by the volume, the solution of the winner determination problem is a bundle that maximizes both value and the sold volume.

Equation (2) states that bidders cannot win bundles of products that have similar products in common (i.e., no overlapping bundles are allocated to the winners). Equation (3) states that no bidder can take more than one bundle at any given valuation (i.e., one bundle at a given time period). Next, Equation (4) deals with time management and prevents delivery preferences of winners to be spread over more than K time periods, which is the length of the delivery horizon. This constraint is explained in the next section. Finally, Equation (5) ensures that all winners receive a complete subset of products, not a portion of these subsets.

4.2 Timber freshness and delivery coordination

As mentioned in the previous section, Equation (4) deals with delivery coordination and timber freshness at the same time. This constraint specifically limits the period of time during which timber delivery to winners can occur. To do so, we define K as the maximum allowed duration (i.e., defined as a number of time period) during which all timber transportation to winners can be planned. The larger this duration, the more flexibility the auctioneer has to plan deliveries, and consequently to plan harvest operations. **Error! Reference source not found.** presents an example of how time is managed. In this example, we assume that all bundles are mutually distinct and any combination of them can be sold. In the bid received, 5 offers (numbered 1 to 5) are represented in the figure. These offers are made for specific delivery during periods 1, 3, 5, 7 and 9 respectively. In this example, the length of the delivery horizon is 5 periods. Consequently, there are only 3 combinations of offers during which delivery can be made within 5 periods: ({offer #1; offer #2; offer #3}; total value=31), ({offer #2; offer #3; offer #4}; total value=32) and ({offer #3; offer #4; offer #5}; total value=28). Consequently, the winning combination of offers is the second one, with a total value of 32.

The length of the delivery horizon can be managed according to the auctioneer's level of flexibility. The smaller the length of the delivery horizon, the fresher is the timber; however, in this case the auctioneer has less flexibility, which can lead to smaller revenue, as studied in the next section. In contrast, the larger the length of the delivery horizon, the more flexibility the auctioneer has to coordinate harvest operations and deliveries. On the other hand, the longer the delivery horizon, the bigger is the risk of timber deterioration.

Granted in practice there is not a large amount of bids that must be processed by the auctioneer (i.e., the duration of the WDP computation is not an issue), the only unknown factor in this winner determination problem, as mentioned earlier, is the effect of the length the delivery horizon on revenue. In the next section, we therefore propose a series of experiments to specifically analyze this aspect.

5 Methodology of experiments

In order to evaluate the performance gap between the proposed time-based combinatorial auction the combinatorial auction without time-management (in this case, we assume that the seller must manage, in conjunction with the winners, the coordination of harvest operations and delivery after the auction), we designed a series of experiments, which is described hereafter.

5.1 Bidders' behaviour

In order to simulate different auctions with a diverse population of bidders, which characteristics are similar in both types of auctions, we first introduce a typical bidder behavior that is defined in terms of time preference and time flexibility, followed by the time dependent valuation function used for the experiments.

Time preference and flexibility

A bidder's time preference reflects the month (i.e., time period) during which he or she wants to receive the timber. In addition, a bidder's time flexibility represents how much he or she is flexible with respect to its delivery time preference. For instance, some bidders may be willing to receive their timber at specific periods of time (e.g., April or May), while others may not have very specific time preferences (i.e., any month of the year).

Time valuation function

According to the concepts of time preference and flexibility introduced previously, the time valuation function is defined by equation (6). This function is based on a normal distribution function, where μ represents the bidders' time preference and σ^2, or variance, presents the bidders' time flexibility. *MAXV* is the maximum value that the bidder is willing to pay at its preferred time.

$$Tvalue(t) = MAXV * e^{-\frac{(t-\mu)^2}{2\sigma^2}} \quad (6)$$

Error! Reference source not found. presents different examples of time valuation functions for a time preference at month 6 (i.e., $\mu = 6$) and three time flexibilities (i.e., σ^2=1.5, 4 and 7). In this example, the value of *MAXV* is 100. Consequently, the value of the time valuation function equals 100 at time $t = \mu = 6$ for three instances of σ^2.

As shown in **Error! Reference source not found.**, for $\sigma^2 = 7$, the bidder is the most flexible because its valuations of month 4, 5, 6, 7 and 8 are almost similar. In other words, this means that this particular bidder's delivery time window is 5-months long, with only a slight loss in value at the beginning and the end of that window. For $\sigma^2 = 4$, the bidder has a smaller preferred delivery time window of months 5, 6 and 7. Indeed for months 4 and 8, the loss in value is much larger than the previous bidder's profile. This preference is even smaller for $\sigma^2 = 1.5$ which corresponds to a delivery time window of basically month 6, with a very large loss in value for the other time periods. Consequently, with a random generation of σ^2 and μ, it is possible to control the generation of very different types of populations of bidders whose preferences can vary greatly.

5.2 Experiments

In the proposed experiments, the seller wants to sell the content of one forest stand, which contains 4 different products that can be sold either as separate items, or as any combination of products. For each individual experiment, 10 bidders were used. Bidders are randomly created with different time preferences, while bidders' time flexibility is controlled for comparison purpose. Note that situations with less than 10 bidders were not studied here. It is possible however, in the case of a low number of bidders, to have no solution for a given level of flexibility (i.e., K). In such situations, we simply assume that the auctioneer can increase K incrementally, until a solution is found. In the extreme case of incompatible bidders' time preferences, the auctioneer can set K to 11 and the model will automatically find a solution, because it is equivalent to the basic combinatorial model. Furthermore, this particular issue is currently part of an agent-based simulation study that deals with the practical and dynamic implementation of this time-based combinatorial auction model.

Furthermore, the general time horizon is 12 periods of one month during which product delivery can be planned. Along the same line, the seller's time flexibility is controlled by the value of *K*. Several values of *K* and σ^2 were also tested. Sets (7) to (10) present the values of K, μ, σ^2, and T that were used in the experiments.

$$K = \{0, 1, 2 \ldots 11\} \qquad (7)$$

$$\mu = \{1, 2, 3 \ldots\ 12\} \quad (8)$$

$$\sigma^2 = \{1.5, 4, 7\} \quad (9)$$

$$T = \{1, 2, 3 \ldots 12\} \quad (10)$$

In order to generate several instances of data to be tested and compared with respect to the two auction models, four products were defined with random volumes, standard valuations, and reserve prices. All combinations of these products were also created. To do so, the volume, standard valuation and reserve price of each combination was calculated based on the sum of the volumes, standard valuations and reserve prices of the products specifically included in the combination. Then, 10 bidders were created for each instance. The maximum value that a bidder is willing to pay (i.e., MAXV) was randomly calculated based on the standard valuation of the combination, for each bidder and each combination. For each bidder, μ is created randomly. For each series of experiments, and as mentioned earlier, σ^2 is the same for all bidders, since these experiments aim at evaluating the effect of σ^2 on revenue. Also all values of *K* between 0 and 11 were systematically tested. Finally, for the time-based combinatorial auction, the specific valuation of each bidder, each combination and each period were calculated using Equation (6). For comparison purposes, in the combinatorial auction with no time management, the valuation of each combination of products was set to the value *MAXV*. In order to improve the significance level of our results, each set of experiments was repeated 30 times, for a total of 1080 optimization results.

6 Results and discussion

Using the sets of data defined in the previous section, the model was tested with CPLEX. The average computation time was 3 minutes and 20 seconds. The performance gap between the time-based combinatorial auction and the combinatorial auction with no time management are shown in **Error! Reference source not found.**.

As expected, the time-based combinatorial auction leads systematically to a slight loss of revenue, due to the decreasing valuation function used to calculate the offers' value. This loss of revenue represents the maximum value the seller can invest in the coordination of harvest and delivery operations after the auction, in conjunction with the winners. In other words, if the value of this loss of revenue is higher than the cost of managing the coordination of deliveries, then the simple combinatorial auction with no time management is better for the seller. This cost can vary greatly according the number of winners and their willingness to find a compromise.

Furthermore, in practice, the value of a forest stand is directly proportional to the volume of timber available. On the one hand, one can expect this loss of revenue to be higher for a larger stand. On the other hand, forest product companies might be more flexible with delivery time as forest stands for sale get larger, because they represent a more significant portion of the supply. Furthermore, although the seller might experience a larger loss of revenue for larger forest stands, he can also expect scale economies with respect to harvest operations. This loss of revenue must therefore be compared to actual coordination cost and to the impact of scale economies with harvest operations.

Similarly, this loss of revenue is also a function of bidders' time flexibility as presented in Equation (6). This aspect is specifically shown in **Error! Reference source not found.**. The first observation is that as *K* increases, the loss of revenue decreases as well, which is perfectly normal (when *K* = 11, time is basically ignored, which is equivalent to the combinatorial auction with no time management). When *K* = 0, in other words when all products are delivered during the same preferred time period, then the average loss of revenue is between 0.5% and 3%, according to the bidders' time flexibility.

The second observation is that when bidders' flexibility is low (i.e., high drop of value when moving away from the preferred period), in other words when σ^2 is small, then the loss of revenue increases up to 3% on average. On the contrary, when bidders have no time preference, then the time-based combinatorial auction is, again, equivalent to the combinatorial auction with no time management).

Figure 7 shows the revenue generated from time-based combinatorial auction. These results show that when the bidders have more flexibility (i.e., high Variance -σ^2), the average revenue generated almost not affected by K. Therefore, the seller can set the value of *K* in order to facilitate harvest operations coordination with other harvest sites. On the other hand, the lower the flexibility of the bidders (i.e., low Variance σ^2), the bigger is the impact of *K* on the revenue.

It also has an impact of revenue variability which increase as bidders flexibility increase. Consequently, there is an element of risk associated with lower bidder flexibility that requires a special attention from the seller. In other words, the seller must adapt the structure of the auction

As a consequence, the profitability of this time-based combinatorial auction is mainly a function of (1) forest stand size and how bidders value larger forest stands; (2) bidders' time preference; and (3) the level of flexibility required by the seller to deliver all products to their winners. Because this latter can be changed by the seller/auctioneer in order to adjust to bidders' time preference, as well as the harvest season, which affects timber deterioration, the time-based combinatorial auction is generally relevant for the auctioneer.

7 **Conclusion:**

This paper proposes a sustainable time-based timber combinatorial auction, which aims to simultaneously allocate multiple products in mixed forest stand to multiple winners, and address the coordination of timber deliveries to their winners. The proposed timber combinatorial auction is economically sustainable. First, all products are sold individually and allocated according to their economic value, with respect to each potential user's market. In other words, a small timber user in a high value market has more control over procurement operations and timber availability if needed. On the contrary to a pure licensed system, in which procurement volumes cannot be easily adjusted, a combinatorial timber auction give a fair chance to participate to every potential timber user. In a combinatorial auction, and for the same reasons, it is more difficult for large forest product companies to gain complete control over timber availability. Finally, because the seller becomes responsible for managing forest operations, the combinatorial auction allows the Ministry of natural resources to exercise high standards for environmentally friendly forest operations as well.

From a logistic point of view, in contrast to other time-based auction systems, time is not part of the product for sale. It is only used as variable of the valuation of the products for sale. Consequently, although this auction system is more complicated for the bidders than the current first-price sealed bid auction, it has many advantages for both the auctioneer and the bidders. First, time-based combinatorial auction can directly address the coordination of delivery of all products between winners, in order to improve the level of timber freshness. When multiple products must be delivered to multiple winners, the coordination of harvest operations and delivery must be carried out. By directly addressing this issue, the time-based combinatorial auction has the potential to simplify complex post-auction negotiations between the winners and the seller. Therefore, by carefully setting up the allowed level of flexibility required to coordinate delivery with both, the bidders expectation and the need for timber freshness, the auctioneer can reduce the cost of planning harvest operations and delivery.

In order to further validate this auction model, future research projects include the implementation of this auction model into a multiple-round auction simulation. Such a project would allow us to evaluate dynamically, and with realistic cost functions, both the level of revenue generated for the auctioneer, but also the logistic usefulness of the auction for the bidder with respect to the coordination of their procurement throughout the year. In this simulation model, all associated costs, such as harvest cost and coordination cost can be measured. The behaviour of the bidders can also be simulated according to bidders' greed and impatience.

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