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Tasseda Boukherroub
Luc LeBel
Angel Ruiz

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Bureaux de Montréal :
Université de Montréal
Pavillon André-Aisenstadt
C.P. 6128, succursale Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

Bureaux de Québec :
Université Laval
Pavillon Palasis-Prince
2325, de la Terrasse, bureau 2642
Québec (Québec)
Canada G1V 0A6
Téléphone : 418 656-2073
Télécopie : 418 656-2624

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A Methodology for Sustainable Forest Resource Allocation: A Canadian Case Study

Tasseda Boukherroub[1,2], Luc LeBel[1,2], Angel Ruiz[1,3]

[1] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT)

[2] Department of Wood and Forest Sciences, 2405, rue de la Terrasse, Université Laval, Québec, Canada G1V 0A6

[3] Department of Operations and Decision Systems, 2325 de la Terrasse, Université Laval, Québec, Canada G1V 0A6

Abstract. This paper addresses the problem of public-owned forest resource allocation observed in Canada. An integrated approach for wood allocation to processing mills operating in a given region is proposed. The approach is based on mill abilities to create value, in terms of economic, environmental, and social benefits. It encompasses three steps: (1) election of sustainable allocation criteria, (2) evaluation of mill performance with regard to the allocation criteria, and (3) allocation of wood volumes according to mill performance. The approach is implemented as follows: first, the international standards, Forest Stewardship Council (FSC) and Global Reporting Initiative (GRI), are used to identify relevant allocation criteria covering the three sustainability dimensions. Second, the Group-Analytic Hierarchy Process method (Group-AHP), a well-known multi-criteria decision making technique, is used to weigh the allocation criteria and evaluate mill sustainability performance. Finally, optimization models are formulated to allocate the wood following two strategies: (1) maximizing the overall created value by all mills, and (2) allocating the wood proportionally to mill performance. The numerical experiments conducted on a real case in the province of Quebec show that integrating sustainable criteria in the evaluation process has a significant impact on the allocation decisions. Lessons learned from this collaboration with the Ministère des Forêts, de la Faune et des Parcs (MFFP) in Québec are presented in order to help other interested researchers and public organizations develop their own roadmap to sustainable public resource allocation.

Keywords. Public-owned natural resources, wood allocation, sustainable performance, value maximization, Group-Analytic Hierarchy Process method (Group-AHP).

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* Corresponding author: Tasseda.Boukherroub@cirrelt.ca

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1. Introduction

The rapid global economic development in the past century led to an unprecedented consumption of natural resources to satisfy the growing demands for food, fresh water, fibre, energy, etc. These natural assets have been perceived for many decades as free and limitless. Nowadays, increasing public awareness of the value of these resources has gradually led governments and businesses to adapt their policies and strategies to match sustainability goals, dealing with the three Ps: Profit, People, and Planet.

In this context, allocating public-owned natural resources to companies competing for the same finite resources is critical. Governments should take into account multiple criteria to allocate the right quantities to the right users while preserving the environment and satisfying the requirements of multiple stakeholders (companies, local communities, population, etc.). To reach these goals, which are often conflicting, sound decisions should be made. This is far from being a trivial task. Maximizing the value created from natural resources and allocating "fair" quantities to companies are the main goals of the government. However, identifying the created value, quantifying it and linking it to sustainability aspects is challenging.

In this paper, we address the problem of public forest resource allocation in the Canadian context, where the forest industry is of primary importance and sustainability goals of high concern. A new approach which integrates all three sustainability dimensions in an optimized wood allocation process is proposed. It specifies relevant sustainable allocation criteria that are used to evaluate processing mill performance. This multi-criteria evaluation is performed by using the Group-Analytic Hierarchy Process (group-AHP), a well-known multi-attribute decision making (MADM) technique. The mill performances are further entered into linear programming (LP) models to determine the optimal allocation for each mill while considering two strategies; maximizing the overall value created by the mills, and allocating wood volumes proportionally to mill performance. The approach is applied on a real case in the province of Québec. Although combining an MADM method with an optimization model has already been proposed in the literature, to the best of our knowledge, this is the first time that such an approach is applied to the forest resource allocation.

The remainder of the paper is organized as follows: the industrial context is described in section 2, a literature survey is presented in section 3, and the generic approach is outlined in section 4. Section 5 introduces the case study, and describes how the approach was implemented. In section 6, we present the experiments and discuss the results. Finally, we conclude and present future research avenues in section 7.

2. Industrial context

More than 400 million hectares of land is covered by forest in Canada, offering rich biodiversity and various ecosystem services (carbon sequestration, water filtration, wild life habitat, etc.). Forests also provide recreation activities (hunting, outdoor activities, etc.) and vital material and spiritual needs for First Nations. It is evaluated that 50% of the Canadian forest could be used for commercial purposes (wood product manufacturing), and 90% of this commercial part is *Crown Land* (NRC, 2014). The wood obtained from public forests is based on supply and forest management agreements (SFMAs) under the jurisdiction of provincial governments. An SFMA authorizes a sawmill or a pulp mill owner to harvest from a specific region, a specific volume of wood of a given species and quality (i.e., cutting rights). Wood allocations specify an annual volume subject to mid-and long-term projections.

The forest industry is an important contributor to the Canadian economy. Indeed, Canada is the second largest exporter of primary forest products in the world, after the U.S. The forest sector is also an important employer in many regions of Canada, particularly in rural and remote communities (NRC, 2014). Over 300 communities across the country are economically dependent on this industry. However, in recent years, the Canadian forest industry has faced major difficulties which led to the closure of more than 300 mills and the loss of approximately 50,000 jobs. High production costs, export tariffs, decreasing demand for paper products, and the U.S. mortgage crisis are some of the factors that have impacted the industry recently.

Due to these problems and other environmental and social issues (clear-cutting, wildlife habitat destruction, First Nations rights, etc.), the public has expressed a lack of confidence in the ability of the governments and forest companies to sustainably manage the public forests. As a result, more economic, environmental and social benefits are expected.

In an attempt to address some of the previously identified issues, the Ministry of Forests, Fauna and Parks (MFFP), which is responsible for managing public forests in the province of Quebec, has adopted a new policy that came into effect on April 1st of 2013. Not only does the new regime give a more important role to government regarding harvest operations planning and execution, but it also modifies the way cutting rights are allocated to mills. Indeed, under the new allocation mechanism, wood volumes that were granted as long-term licenses to mills have been reduced to 75% of the initial volumes. The remainder is auctioned to create market opportunities for new players, allow for new business model development, favour greater efficiency, and promote the emergence of innovative products and services which are beneficial to the economy, society, and the environment.

These dramatic changes led to a reduction of public wood available in the province, and this situation has also created tough competition between forest companies for which wood supply from public forests becomes even more critical. It also poses a real challenge to the government who must allocate finite wood quantities while attaining sustainability goals on the one hand, and preserve forest industry stability and profitability on the other hand. At present, the wood allocation process relies on broad rules that maintain status quo and historical privileges.

3. Literature survey

Wood allocation is an important decision in the context of public forest management. It entails determining the right volumes of forest resource to allocate to different users (sawmills, pulp and paper mills, etc.) by government agencies. Such a problem applies also for other natural resources, such as water (Reca *et al.*, 2001; Messner *et al.*, 2006; Letcher *et al.*, 2007; Zhou *et al.*, 2014) and fisheries (Morgan, 1995; Stewart *et al.*, 2009; Poos *et al.*, 2010), as well as non-natural resources such as spectrum frequencies (communication for radio, television, cellular telephones, etc.) (McMillan, 1994), and airport slots (Ball *et al.*, 2006).

In the context of sustainable forest management, the problem of allocating public wood to companies must take numerous criteria into account (Marinescu *et al.*, 2005). Indeed, governments seek to generate maximum economic and social benefits from public forest resources, while at the same time ensuring the protection and preservation of the environment. In addition, multiple constraints should be considered, such as respecting the total allowable cut that ensures long-term sustainable use of the forest resource, allocating the right species (e.g., spruce, pine, fir, popular, etc.) and the right log quality (saw log, pulp log, etc.) for the right uses (lumber products, pulp and paper, etc.), considering the processing capacities of the mills, etc.

The problem of wood allocation, especially in the context of sustainable forest management received little interest in the literature. For many years, specialists have recognized the importance of wood allocation decisions, but those decisions were treated in integrated forest management and wood products processing models (Marinescu *et al.*, 2005). Therefore, early models (late 1960s and into the 1970s) that tackled wood allocation decisions were extensions to traditional models dealing with forest regulation and harvest scheduling (e.g., Pearse and Sydneysmith, 1966; Thompson and Richards, 1969; Lönner, 1968; Carlsson, 1968; Westerkamp, 1978). Lastly, most of these models are based on a mono-objective LP approach focusing solely on one economic criterion.

More recently, Marinescu *et al.* (2005), Bone and Dragicevic (2009) and Ouhimmou *et al.* (2013) have developed multi-criteria decision making models to optimally allocate wood to different forest companies. The model developed by Marinescu *et al.* (2005) maximizes the profit and employment values generated by each harvested area in the forest, by each forest company, when transforming the wood into lumber products. The calculations were performed by a sawmilling optimization sub-model that uses the characteristics of input logs (i.e., dimensions), production parameters, lumber products, and markets to find the maximum profit and the associated working hours for each company. Then, a DEA (Data Envelopment Analysis) (Charnes *et al.*, 1978) sub-model is used to determine the efficiency of each forest company with regard to the profit and employment it generates. The scores obtained are then used in a mixed integer programming sub-model that determines the optimal assignment of harvesting areas to the companies, while respecting the maximum annual allowable cuts (AAC) and the processing capacities. The model has been applied to a case study of three forest companies in British Columbia, Canada.

In this model only sawmilling activities (i.e., lumber production) were considered. Moreover, only two quantitative criteria (profit and employment) were integrated in the allocation process. In this regard, Marinescu *et al.* (2005) reported that computational effort became important when other criteria were added. Finally, the characteristics of wood considered in the model are restricted to the log dimensions. Moreover, other characteristics such as species and log quality are important as they impact production yields and costs, as well as the quality of final products and the generated profit.

Bone and Dragicevic (2009) developed an Intelligent Agent Model (IAM) for allocating, spatially and over time, natural resources while taking multiple objectives into account. The model integrates agent-based modeling in a GIS (Geographic Information System) environment with a reinforcement learning algorithm - a heuristic used to reward decisions made by individual agents that lead to achieving specific objectives. The model was implemented in the context of forest management on a study site in British Columbia, Canada. Each agent represents a forest company that learns when and where to harvest trees in a manner that maximizes its economic return while minimizing the ecological impact to the surrounding landscape (average age of harvested trees and area size over wood is harvested). This allows each agent to explore their jurisdiction within the landscape to extract a resource. The evaluation of these actions is recorded as an attribute of the landscape, and over time, is used to help forest companies learn where the most beneficial locations are for extracting resources.

The model proposed by Bone and Dragicevic (2009) assists forest companies in selecting the “best” harvesting areas that maximize “utility function” regarding their economic returns while considering ecological aspects. However, the model does not fit government decision-makers’ needs regarding which wood volumes to allocate to companies in order to maximize generated benefits.

Ouhimmou *et al.* (2013) developed a multi-objective mathematical programming model for selecting harvesting areas and allocating wood to mills over several time periods. They considered multiple criteria such as transportation distance and cost, budget for sylvicultural prescriptions, percentage of certified wood, etc., and formulated the sum of the differences between the targeted values and the real values of those criteria as an objective function to be minimized. In addition, the authors extended their model to include the minimization of spatial dispersion between harvesting areas in order to promote the selection of harvesting areas within clusters of high density. The model was tested in several regions in Quebec, Canada. Even though this model assists the government in selecting harvesting areas that satisfy a compromise between several spatial, quality and economic criteria, it does not explicitly maximize the value created by the mills.

We can conclude that there is a lack of models in the literature which effectively address the problem of wood allocation with the aim of maximizing the value created from processing the wood. Yet, this is a problem that public officers must resolve on regular and recurrent basis. In Quebec alone, the value associated with this type of decision is worth in excess of 13 billion dollars. Therefore, new approaches and models need to be developed to address the problem. Such approaches and models should be capable of handling multiple criteria (economic, environmental, and social), while at the same time, offering flexible and user-friendly decision support tools for decision-makers.

4. Proposed approach

Let us first define the concept of “value” that may have various meanings. In this work, as mentioned in previous sections, value concerns the range of economic, environmental, and social benefits generated at a local economic level (regional level for example) for various stakeholders (employees, local communities, First Nations, the ecosystem, etc.), through processing wood (harvesting, transportation, manufacturing, etc.) by forest companies (sawmills, paper mills, etc.).

However, assessing the value created by a given mill is not trivial. This requires quantifying the economic, environmental and social benefits generated. The value should also be effectively linked to the allocation decision process, and then maximized. Furthermore, mills manufacturing various products and creating less or more value should be allocated the right quality and quantity of wood.

Different approaches could be adopted to address the aforementioned problem. In this study, we combine tools from multi-criteria decision making and optimization fields. However, before choosing specific decision making tools, it is important to understand and target specific sustainability goals (Boukherroub et al., 2015). Therefore, our approach proposes to integrate three main steps: (1) allocation criteria specification, (2) multi-criteria performance evaluation, and (3) value maximization and wood allocation. In this section we provide a generic description of each step. A detailed description will then be presented in the next section along with a presentation of the application of the approach on a real case from the province of Quebec, Canada.

- ***Step 1**: Allocation criteria specification*

In order to evaluate the value created by a given mill, several criteria characterizing the economic, environmental, and social benefits generated must first be specified. Then, experts and decision-makers can evaluate the performance of the candidate mills based on those criteria used as allocation criteria. To elicit consistent criteria covering the three sustainability dimensions, recognized international standards represent an obvious starting point. These standards (e.g., Global Reporting Initiative) have gained widespread acceptance from government agencies, forest companies and NGOs.

- ***Step 2**: Multi-criteria evaluation*

We adopt the aggregative multi-criteria approach to allow for expert evaluation of candidate mills. Such an approach allows setting priority weights among allocation criteria, and computing aggregated scores for the mills. The aim is to capture the value created by each mill. Methods derived from multi-attribute utility theory such as multi-attribute utility (MAUT) (Keeney and Raiffa, 1976), additive utility function (UTA) (Jacquet-Lagrèze and Siskos, 1980), and AHP (Saaty, 1980) are particularly appropriate for this type of evaluation.

- ***Step 3**: Value maximization and wood allocation*

Once the score of each mill has been computed, wood allocation should be calculated such that the mills receive wood proportionally to their performance (i.e., the value it creates) and the value maximized. For example, the volumes to allocate could be weighted by the scores of the mills, and the resulting weighted sum formulated as an objective function to be maximized in a mathematical programming model. Simulation-based models are other tools that could be used.

In the next section we describe the implementation of the approach and show its practical value based on a real case study.

5. Implementing the proposed approach

This section is divided into two parts. First, we introduce the case study. Then, in the second part, we show how we implemented our approach. All the data comes from a real case provided by MFFP. Therefore, for confidentiality reasons, the names of the region and the companies under study are not disclosed, and the results are all scaled by coefficients.

5.1 Case study

The region of the case study is located in the province of Quebec, Canada. We refer to it as “R” throughout the rest of the article. It has an area of approximately 28,500 km^2, and 85% of the territory is covered by forests. Roughly 60% of the forest is public while the remainder is private. The forest sector is an important contributor to the local economy in region R. For instance, in 2004, more than 5,000 jobs were related to forest activities (forest operations and primary and secondary transformation), and in 2005, the sector contributed to more than 9% of the regional GDP. However, in the last decade, the number of mills operating in R has dramatically decreased due to the forest sector crisis. This led to the loss of hundreds of jobs.

Currently, 20 mills manufacturing various wood products such as lumber, paper, shingles, OSB panels, etc. (see Appendix), have supply agreements with the government. Wood species available mainly consist of two families of conifers (softwood) and two families of deciduous (hardwood). Each family species possesses different characteristics making them suitable for specific industrial uses (see Table 1). We will refer to these specific uses as “qualities.” The species and qualities required for each of the 20 mills, and the main products they manufacture are presented in the Appendix.

Table 1: Wood species and "qualities" available in region R

	Quality		
Wood species	Saw log	Veneer log	Pulp log
SPF (fir, spruce, pine, larch)	✓		
THUJ (thuja)	✓		
POPL (poplar)	✓	✓	✓
HRDW (maple, yellow birch, other)	✓	✓	✓

Several ecological aspects warrant close attention. The public territory in the study region is rich in wildlife and shelters various endangered species such as caribou. It also offers favourable conditions for various recreation and outdoor activities. Finally, maintaining harmonious relationships with First Nations is also an important issue. In this regard, the government has ratified several agreements on trapping and hunting practices with the First Nations community living in R.

This challenging context offers a perfect opportunity to validate our approach. We therefore decided to work in close collaboration with MFFP to provide priority weights among allocation criteria and evaluate mill performance with respect to the elected criteria. Two experts, referred to as "EX1" and "EX2," participated in the project. "EX1" is presently responsible for wood allocation in several regions in Quebec, including region R, and"EX2" is responsible for estimating mill demand for wood from the public forest.

5.2 Applying the proposed allocation approach

EX1 and EX2 first validated the generic approach. Then, they provided us with detailed data pertaining to mill performance, wood consumption and wood availability. The implementation of each step of the approach was discussed with EX1 and EX2 throughout an iterative process.

5.2.1 Allocation criteria specification

We relied on FSC (Forest Stewardship Council) and GRI (Global Reporting Initiative) standards to select relevant allocation criteria. FSC is an international certification and labelling system dedicated to promoting responsible forest management of the world's forests (FSC, 2012); and GRI offers an international reference for measuring and reporting economic, environmental, and social performances (GRI, 2011). However, while FSC is mainly concerned with operations and practices held in the forest, GRI is applicable to the entire value chain. Moreover, GRI offers several sustainability indicators. In order to utilize the best aspects of both standards, we combined principles from the two standards.

During the selection process, we made sure that each chosen criterion was qualitatively or quantitatively measurable. In addition, we applied rules suggested in the literature (Keeney and Raiffa, 1976; Roy, 1985) to ensure the consistency of the criteria: representativeness, redundancy, dependency, manageability (reasonable number of criteria), etc. To validate the criteria, these were presented to EX1 and EX2, one forest industry expert, and two FSC specialists. At the end of this process, nine criteria equally covering the three sustainability dimensions, i.e., three criteria for each dimension were selected (Table 2).

Table 2: Proposed allocation criteria for each sustainability dimension

Dimension	*Allocation criterion*
Economy (Eco)	***Eco.1***: Value adding product/service diversification and benefits for locally based suppliers and industries
	Eco.2: Generation and distribution of direct economic value
	Eco.3: Financial health/stability and operations efficiency
Environment (Env)	***Env. 1***: Protection of biodiversity and species-at-risk, and the ecosystem
	Env. 2: Reduction and treatment of significant air emissions, pollutants and solid waste
	Env. 3: Reduction of water use and treatment of wastewater
Society (Soc)	***Soc. 1***: Diversity/equal opportunities and work conditions
	Soc. 2: Employment and training/education opportunities
	Soc. 3: Transparent communication and engagement with First Nations and local communities

The economic dimension reflects the impact of industrial activities on the local economy in terms of product and service diversification, benefits for locally based suppliers and industries, and direct economic value generated and distributed. It also takes into account financial performance, and operations efficiency. The environmental dimension includes the impacts of the activities on living and non-living natural systems, including the ecosystem, land, air, and water. Finally, the social dimension includes the impacts on directly affected stakeholders (employees, local communities, and First Nations).

We did not include basic criteria such as human rights (child labour, forced and compulsory labour, etc.), as these requirements are strictly abided to forest companies in Quebec. Moreover, criteria related to non-compliance with law and regulations are treated as exclusion criteria.

5.2.2 Multi-criteria evaluation

To compute the scores of the 20 mills, we adopted Group-AHP (Saaty, 1980) documented both in the literature and in practice (Taslicali and Ercan, 2006). Group-AHP has been widely applied for preference analysis in complex, multi-attribute problems (Varis, 1989). It has also been applied for strategic planning in a forest decision context (Schmoldt *et al*. 2001; Mardle *et al.*, 2004, Ananda, 2007; Ananda and Herath, 2009).

Group-AHP describes a general decision making problem by decomposing it into a multi-level hierarchical structure of objectives, criteria, and alternatives (Saaty, 1990). The preferences for the alternatives, the criteria, and the objectives are compared in a pairwise manner by using judgement matrices. Numerical operations are then performed based on methods first formalized by Saaty (1980) to derive quantitative values from these comparisons, i.e., the weights of the criteria and the scores of the alternatives. The alternatives' final scores are determined by aggregating the weights and scores (weighted sums). Finally, to ensure the consistency of the pairwise comparisons, a consistency ratio is calculated and compared to a standard value.

Group-AHP is perceived as suitable for our problem for the following reasons: (1) it allows for compensation between criteria, and in our case, it may be difficult for the mills to be "best in class" in regards to all allocation criteria (Table 2). (2) Group-AHP enables the integration of both qualitative and quantitative criteria. And (3), it naturally considers multiple decision-makers in the evaluation process.

Figure 1 shows how the principles of Group-AHP were applied to the case study. ***Level 0*** describes the overall objective of the analysis, which is to evaluate the performance of the 20 mills. ***Level 1*** presents the experts involved in the analysis (i.e., EX1 and EX2). ***Level 2*** encompasses the three dimensions of sustainability (*Eco*, *Env*, and, *Soc*). ***Level 3*** contains the nine allocation criteria (*Eco.1, Eco.2, Eco. 3, Env.1, Env.2, Env.3, Soc.1, Soc.2,* and, *Soc.3*). ***Level 4*** includes the four tree species available for harvesting in region R. We use them to cluster together mills processing the same species. By doing this, we compare only mills within the same cluster. Finally, ***Level 5*** encompasses the candidate mills.

The pairwise comparison starts from Level 2 and continues on to Level 5. The relative importance of each sustainability dimension, criterion and alternative is quantitatively expressed by each expert within each level. Within Level 5, the mills grouped in the same cluster are compared pairwise according to each of the 9 criteria (Level 3). The species (Level 4) are assigned the same weight as they are only used to cluster mills processing the same species. The final score of a given mill with regard to the species it processes is determined by EX1 and EX2, by calculating first the weighted sum of the mill score with respect to each criterion (Level 3) and the weights of these criteria. By doing this, an aggregated economic, environmental, and social score is obtained by the mill at Level 2. The final score of the mill is then obtained by computing the weighted sum of the economic, environmental, and social scores and the weights of the three sustainability dimensions (Level 2).

To determine the aggregated score of a mill with regard to the joint evaluations performed by EX1 and EX2, the geometric mean is used to derive aggregated judgment matrices at each level. Thus, the element c_{ij} of a new judgement matrix is the geometric mean of the elements a_{ij} and b_{ij} of EX1 and EX2 judgment matrices, respectively. Here the same importance is given to EX1 and EX2. When equal importance is given to voters in a group, Aczél and Saaty (1983) showed that the geometric mean is the proper way to synthesize judgments.

5.2.3 Value maximization and wood allocation

Linear programming was used to determine the optimal wood volumes to allocate to the 20 mills. We formulated two LP models (*LP1*and, *LP2*) to assess two different allocation strategies: LP1 maximizes the value created by all mills, while LP2 attempts to allocate wood to the mills according to their performance. In the next paragraphs we first present the set of indexes, parameters and constraints common to the two models. Then, we specify the constraints of LP1 and LP2 and the two objective functions.

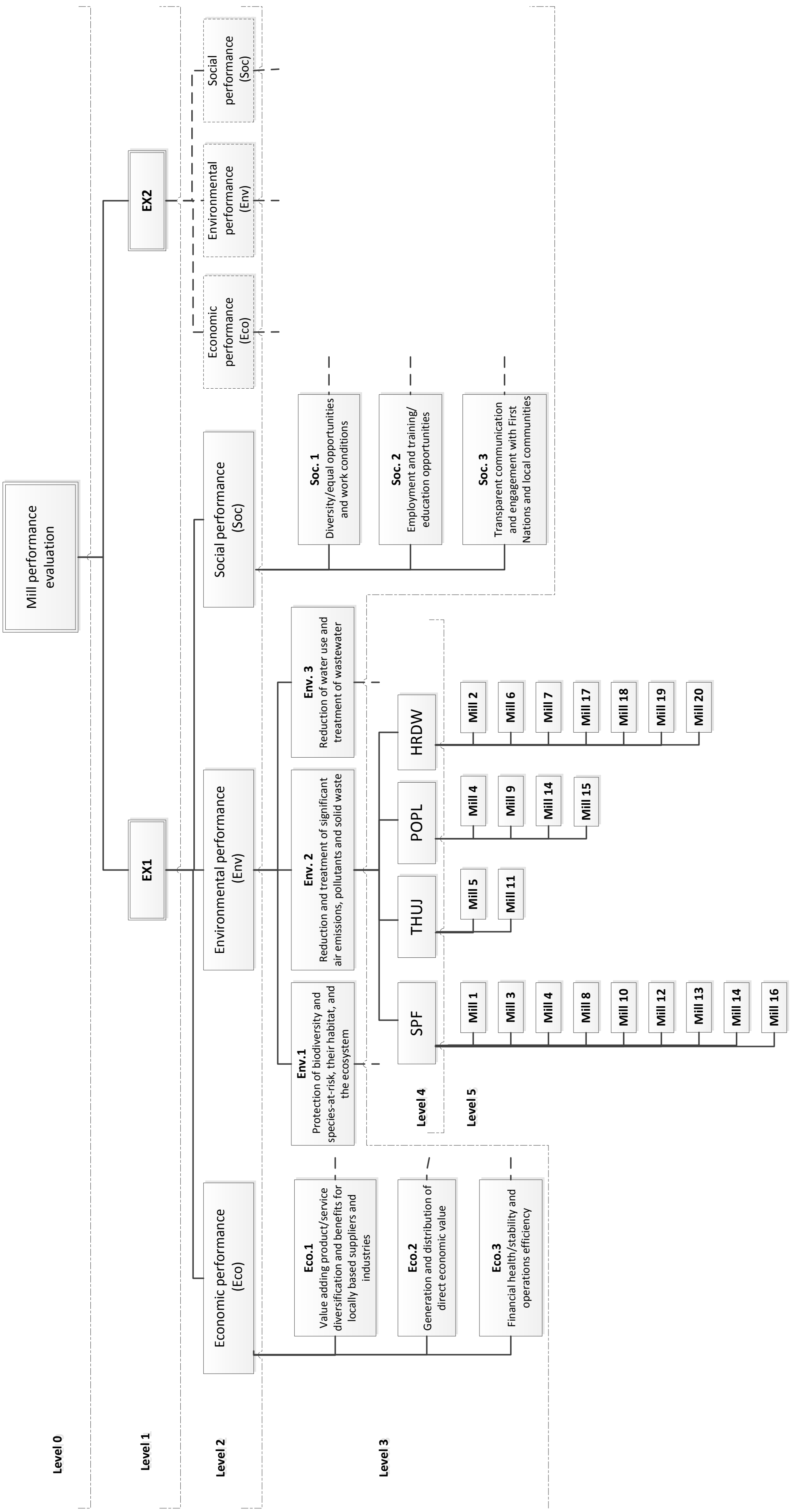


Figure 1: Mill evaluation using Group-AHP

- **Sets of indexes**

J_S Set of mills processing veneer log and/or saw log and pulp log qualities. We will refer to all the plants within this set as "sawmills."
$J_S = \{Mill_1, \dots, Mill_5, Mill_8, \dots, Mill_{16}, Mill_{18},\ Mill_{20}\}$

J_P Set of mills processing only pulp log quality. We will refer to all the plants within this set as "pulp mills." $J_P = \{Mill_6, Mill_7, Mill_{17}, Mill_{19}\}$

J Set of mills,$J = J_S \cup J_P$

E Set of wood species. $E = \{SPF, THUJ, POPL, HRWD\}$

Q Set of qualities.

$Q = \left\{SL^{spf}, SL^{thuj}, VL^{popl}, SL^{popl}, PL^{popl}, VL^{HRDW}, SL^{HRDW}, PL^{HRDW}\right\}$

$Q_{(e)}$ Set of qualities of species e. E.g., $Q_{(POPL)} = \{VL^{popl}, SL^{popl}, PL^{popl}\}$

Q_S Set of wood qualities allowable to the set of plants withinJ_S

Q_P Set of wood qualities allowable to paper mills set of plants withinJ_P

- **Décision variables**

Y_{qj} Volume of quality q to allocate to $Mill_j$

X_{ej} Volume of species e to allocate to $Mill_j$

- **Paramètres**

A_q AAC for quality q

C_{ej} Processing capacity of mill j for species$e$.

$\underline{V}_{qj}$ Minimum volume of quality q that should be allocated to $Mill_j$ regardless of its performance. This lower bound is fixed by MFFP.

S_{ej} Score obtained by$Mill_j$within the group of species$e$

- **Contraints**

The volume of species to allocate to each mill should be equal to the sum of the volumes of all qualities of that species allocated to the mill.

$$X_{ej} = \sum\nolimits_{q \in Q_{(e)}} Y_{qj} \qquad \forall \ e \in E, \quad \forall \ j \in J \quad (1)$$

The total volume of a quality allocated to the mills should not exceed the AAC.

$$\sum\nolimits_{j} Y_{qj} \ \leq \ A_q \qquad \forall \ q \in Q \quad (2)$$

The volume of species allocated to each mill should be less or equal to its processing capacity.

$$X_{ej} \leq C_{ej} \qquad \forall \ e \in E, \quad \forall \ j \in J \quad (3)$$

The wood volume to allocate to each mill should be equal to or greater than its prefixed minimum volume.

$$Y_{qj} \geq \underline{V}_{qj} \qquad \forall \ q \in Q, \quad \forall \ j \in J \quad (4)$$

Mills should be allocated the right qualities for each wood species and in the right proportions:

- *POPL:* sawmills should not be allocated more than 45% for the quality pulp log (PL^{popl}). Constraints (5).
- *HRDW:* sawmills should be allocated only veneer log and/or saw log qualities (VL^{hrdw}, SL^{hrdw}, respectively) whereas pulp mills should be allocated only pulp log quality (PL^{hrdw}). Constraints (6) and (7).

$$Y_{VL^{popl}j} + \ Y_{SL^{popl}j} \geq 0.55 * X_{POPLj} \qquad \forall \ \ j \ \in J_S \quad (5)$$

$$Y_{VL^{hrdw}j} + \ Y_{SL^{hrdw}j} = X_{HRDWj} \qquad \forall \ \ j \ \in J_S \quad (6)$$

$$Y_{VL^{feui}j} + \ Y_{SL^{feui}j} = 0 \qquad \forall \ \ j \ \in J_P \quad (7)$$

The decision variables should be continuous and positive.

$$Y_{qj} \geq 0 \qquad \forall \ q \in Q, \ \forall \ \ j \ \in J \quad (8)$$

$$X_{ej} \geq 0 \qquad \forall \ e \in E, \forall \ \ j \ \in J \quad (9)$$

- ***LP1: maximizing the expected value***

The objective function aims to maximize the sum of the wood volumes allocated to mills weighted by their scores (equation (10)). LP1 attempts to satisfy as much as possible the mills having the highest scores.

$$Max f_1 = \sum_j \sum_e S_{ej} * X_{ej} \tag{10}$$

- ***LP2: allocating the wood proportionally to mill performance***

Let us introduce variables $\overline{d}_{ije}$ and $\underline{d}_{ije}$, representing respectively the deviations "up" and "down" from the ideal proportionality between volumes allocated to mills and their performances. The objective function minimizes the sum of the normalized "up" and "down" deviations, and the sum of unallocated volumes (in %). By integrating the residual volumes, i.e., the unallocated volumes, into the objective function, the model finds the best values proportional to mill performance while ensuring that the AAC is all allocated (up to the mill processing capacities). The objective function to be minimized is given by equation (11).

$$Min f_2 = \sum_i \sum_j \sum_e \frac{\left(\overline{d}_{ije} + \underline{d}_{ije}\right)}{M} - \sum_q \sum_j \frac{Y_{qj}}{A_q} \tag{11}$$

Subject to the constraints:

$$\underline{d}_{ije} - \overline{d}_{ije} = S_{ej} * X_{ei} - S_{ei} * X_{ej} \qquad \forall i \in J, \forall j \in J, \qquad i \neq j, \forall e \in E \tag{12}$$

$$\underline{d}_{ije}, \overline{d}_{ije} \geq 0 \qquad \forall i \in J, \forall j \in J, i \neq j, \forall e \in E \tag{13}$$

M is a big number.

6. Experiments and results

The Group-AHP evaluation was supported by Expert Choice software, and the LP models solved with IBM ILOG CPLEX Optimization Studio 12.5. EX1 and EX2 first evaluated the 20 mills on Expert Choice. We then exported the results into CPLEX to solve the two LP models.

6.1. Group-AHP evaluation

Figures 2, 3, and 4 show the weights in percentage assigned to the three sustainability dimensions by EX1, EX2, individually, and in an aggregated manner, respectively. We observe that both EX1 and EX2 pay significant attention to the economic dimension. However, whereas EX1 places environmental concerns at the same level as economic ones and gives very low importance to social concerns, EX2 pays little attention to the environmental dimension and much more attention to the social one. The aggregated weights reflect, as expected, a compromise between EX1 and EX2 judgements.

Figures 5, 6, and 7 show the normalized scores in percentage given to mills within the cluster *SPF*. As shown in the results, the evaluations made by EX1 and EX2 yielded very different scores. The mill scores produced by EX1's evaluation range from ~26% to ~4.5%, and from ~18.5% to ~6.5% in the case of EX2. Thus, according to EX1's judgements, the "best" mill (mill 4) performs ~6 times better than the "worst" mill (mill 1),while according to EX2, the best (mill 13) performs ~3 times better than the worst one (mill 14). The aggregated scores of EX1 and EX2 shown in Figure 7 constitute a compromise between the individual scores.

- ***Sensitivity analysis***

As we can observe, evaluations by different experts lead to different weights and scores. Therefore, it becomes of the upmost importance for the approach's credibility, being able to evaluate how the scores and rankings of the mills evolve when weights assigned to the economic, environmental and social dimensions are changed. To illustrate this point, we analyze aggregated scores and rankings for mills within the SPF cluster. We consider two scenarios:

- *Scenario 1:* we consider solely the economic dimension. Therefore, only the criteria related to this dimension are evaluated. This scenario closely fits the current practices of the government.
- *Scenario 2:* we assign equal weights to the economic, environmental and social dimensions (1/3 each).

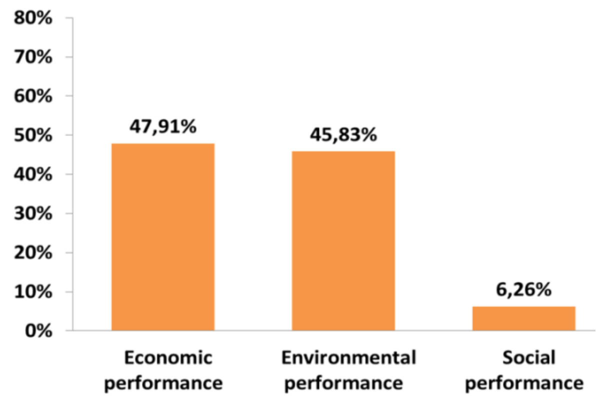


Figure 2: Weights of sustainability dimensions obtained by EX1 (%)

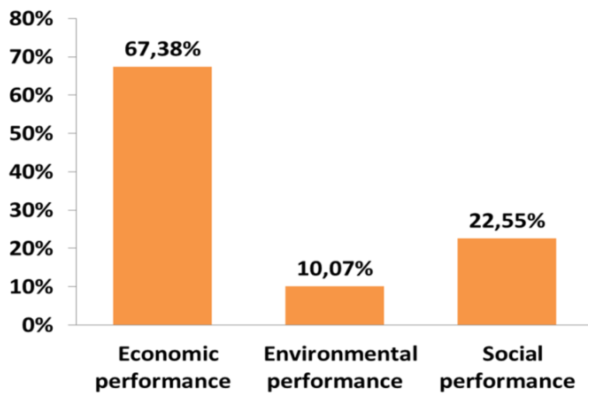


Figure 3: Weights of sustainability dimensions obtained by EX2 (%)

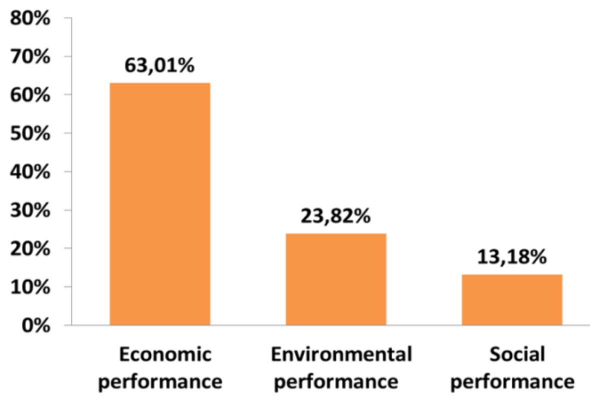


Figure 4: Aggregated weights of sustainability dimensions obtained by EX1 and EX2 (%)

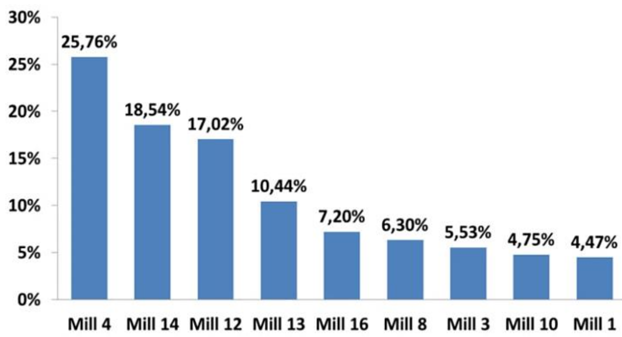


Figure 5: Scores of mills processing SPF obtained by EX1 (%)

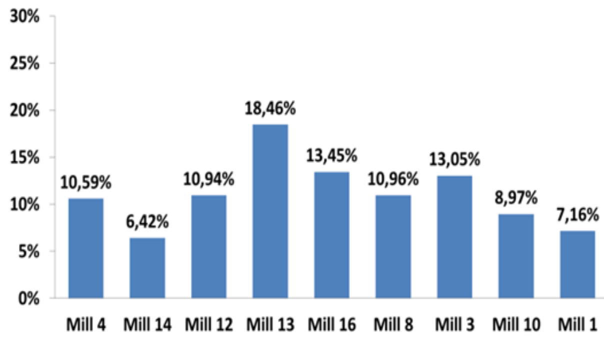


Figure 6: Scores of mills processing SPF obtained by EX2 (%)

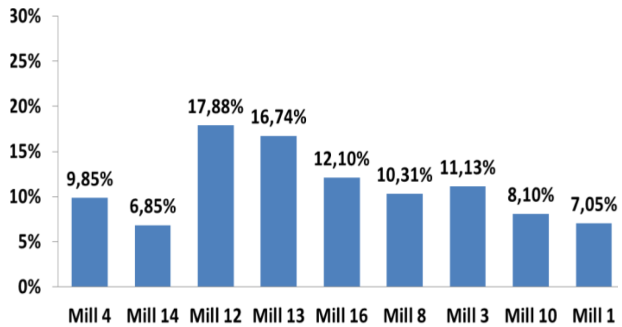


Figure 7: Aggregated scores of mills processing SPF obtained by EX1 and EX2 (%)

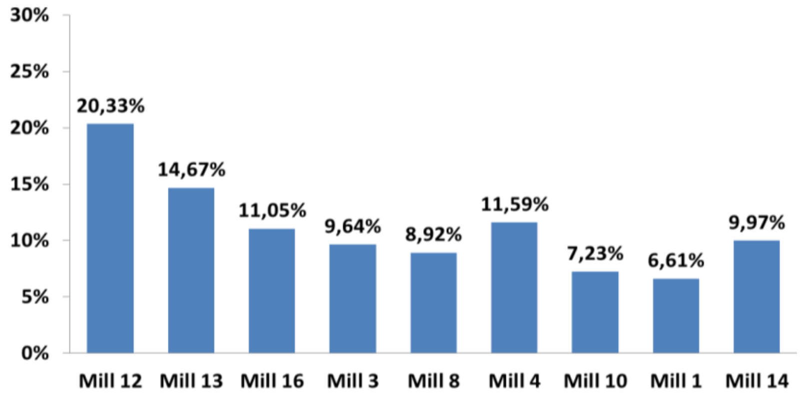


Figure 8: Aggregated scores of mills processing SPF obtained by EX1 and EX2 when only the economic criteria are considered in the evaluation (%)

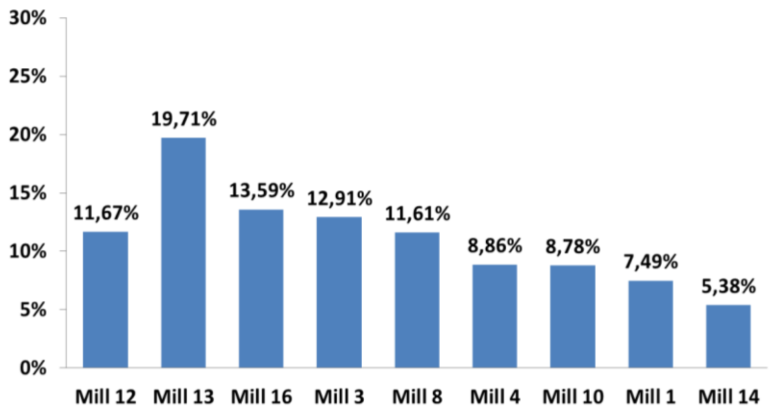


Figure 9: Aggregated scores of mills processing SPF obtained by EX1 and EX2 whenthe three sustainability dimensions are balanced (%)

The results for scenarios 1 and 2 are shown in Figures 8 and 9, respectively. In *scenario 1*, the ranking and the score of the previous best mill (mill 12) changes significantly: it is now ranked in 4th place and its score changed from 17.8 to 11.67%. On the other hand, mill 13 has moved from rank #2 to rank #1 and its score has changed from 16.74% to 19.71% (Figure 8). The remaining mills keep their previous rank - their scores having only slightly changed.When attempting to reach a balance between the three sustainability dimensions (*scenario 2*), mill 4 and mill 14 obtain better scores and rankings (Figure 9). Mill 4 is ranked 3rd instead of 6th and mill 14 is ranked 4th instead of 9th.

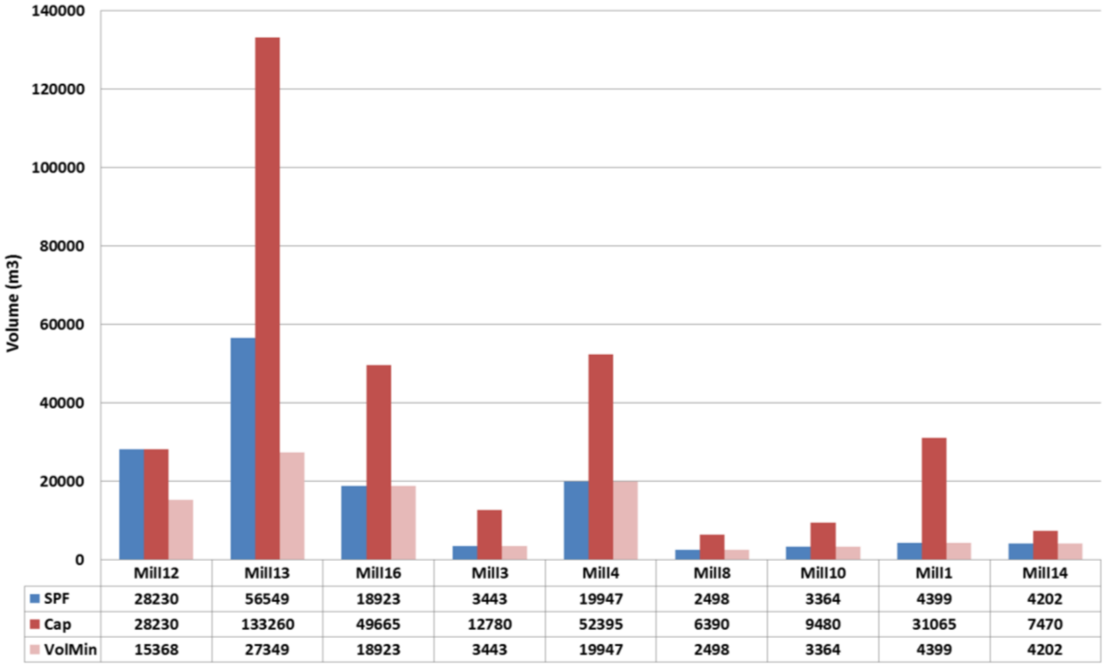
6.2 Numerical results produced by the LP models

We consider the mill scores produced by aggregating evaluations of EX1 and EX2 to solve the two LP models. We will use the specific cluster SPF to discuss the results.

Figures10 and 11 show the volumes of SPF species allocated to each mill according to LP1 and LP2, respectively.

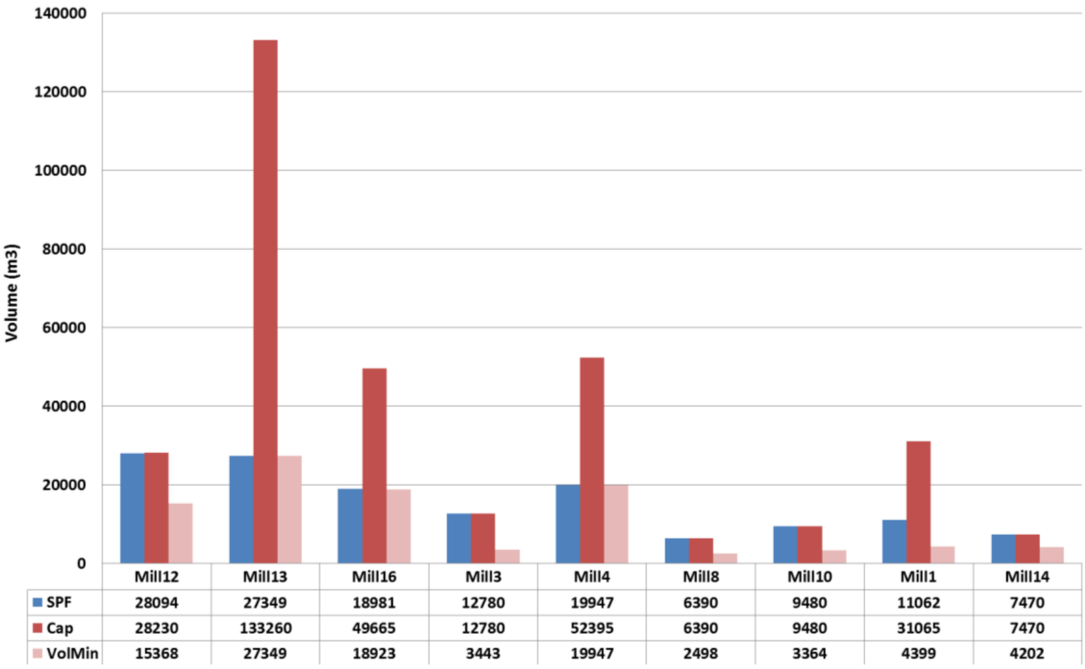
The two models lead to very different results. The optimal solution to LP1 is characterized by ensuring that each mill has minimum volumes, and then allocating the remaining volume to the best mill first, according to its processing capacity.Then volumes are allocated to the second mill, and so on, until all the AAC is allocated (Figure 10). Therefore, maximizing the created value works according to the mill ranks rather than scores. This strategy would perform poorly in a case where mills have very similar performances, as the best mill will always be favoured at the expense of all the rest regardless of how well they perform.

On the other hand, LP2 ensures, using the slack variables $\overline{d}_{ije}$ and $\underline{d}_{ije}$, that the mills are allocated wood volumes which are proportional to their performance (Figure 11). Perfect proportionality could be reached if the volumes to be allocated were not constrained by mill processing capcities and minimum volumes. Unlike the first strategy, this strategy does not maximize the overall created value. Indeed, LP2 achieves a "created value" (measured by the mathematical expression of f_1) which is 7.60% lower than the maximal (optimal) value reached by LP1. This could be interpreted as missing opportunities for creating employment, profit, value adding product/service creation, etc., in the short-term. However, the gap is narrow. Moreover, concentrating wood in a reduced number of mills will certainly weaken competition and, in the long-term, will provoke several mills to close, which is contrary to the sustainable principles. We can therefore conclude that adopting the second strategy would be more appropriate as the goals of maximizing the created value and allocating wood proportionally to mill performance are both reached with minimum deviations from the optimal targeted values.



	Mill12	Mill13	Mill16	Mill3	Mill4	Mill8	Mill10	Mill1	Mill14
SPF	28230	56549	18923	3443	19947	2498	3364	4399	4202
Cap	28230	133260	49665	12780	52395	6390	9480	31065	7470
VolMin	15368	27349	18923	3443	19947	2498	3364	4399	4202

Figure 10: Results of LP1 for mills processing SPF species



	Mill12	Mill13	Mill16	Mill3	Mill4	Mill8	Mill10	Mill1	Mill14
SPF	28094	27349	18981	12780	19947	6390	9480	11062	7470
Cap	28230	133260	49665	12780	52395	6390	9480	31065	7470
VolMin	15368	27349	18923	3443	19947	2498	3364	4399	4202

Figure 11: Results of LP2 for mills processing SPF species

6.3. Lessons learned and recommendations

This article presents a first implementation of our approach and the preliminary results obtained based on data from a real case. Our experience with MFFP allows us to extract valuable insights which can help public organizations move forward in the integration of sustainability into their resources allocation processes. The following paragraphs summarize our main observations and recommendations.

To implement the proposed decision support system and enable an allocation process based on sustainability performance data on mill performance regarding specific targeted criteria must be collected in a continous manner. Therefore, it is important that governmental officers implement scoreboard systems and performance indicators, and continuously collect and update the data to support the evaluation processes and consider mill performance evolution over time. Furthermore, developping such “sustainability measurement” culture will incite forest companies to implement good environmental and social practices and will therefore improve their sustainable performance. To coax companies in this direction, we suggest the process to be used in a recurrent manner and that it develops a kind of “memory” able to evaluate performance improvements rather that absolute values.

To ensure that the “right” weights are assigned to the “right” sustainability criteria, policy makers should set general guidelines reflecting governmental sustainability policy and vision to provide experts with a common understanding of sustainable forest resource management. In this regard, the application of a performance based allocation process would require communicating the selected performance criteria as well as the adopted methodology to forest companies. These criteria should be known well in advance before applying such a process on a regular basis.

The two allocation models led to very different solutions, but these solutions correspond to rather similar expected values. While the value maximization model behaves according to a “all or nothing” rule based on mill ranking, the proportional-to-performance model ensures “equity” between mills, as they are “rewarded” proportionally to their performance. The second model is therefore more appropriate. However, further research is necessary to improve and reach the objective function to better reflectthe interest of the government.

Finally, the implementation of a performance based allocation process will certainly have an impact on the whole network of industry sourcing wood from public forests. In particular, we refer to the interactions between the mills with cutting rights that are allocated wood volumes and value-adding mills that do not have cutting rights, but which are the customers of log processing mills, and are therefore directly impacted by upstream decisions. We intend to analyze the impact of the allocation decisions produced by the LP models on the production needs of those downstream mills, and how the latter could be considered in the allocation process in order to optimize the whole forest product value chain. Again, additional research, which could merge game theory and agent simulation approaches, is required to try and forsee the kind of consequences and the possible strategies developped by organizations forthis new paradigm.

7. Conclusion

In the current context of forest resource scarcity and high industrial competitiveness, and due to public requirements on sustainable forest resource management, the allocation of public forest resources for industrial usage merits close attention.

In this paper we have proposed an allocation decision-making approach based on mill sustainability performance. The approach was applied to a real case study in the province of Quebec, Canada, in partnership with the government agency in charge of wood allocation. Sustainability criteria based on GRI and FSC standards were selected, and used to evaluate mill performance by means of a multi-criteria tool (Group-AHP). We have developed an optimization model that identifies actions which maximize the sustainable value of allocated wood.

The results showed the relevance of considering environmental and social criteria in the evaluation process, in addition to economic ones. The following is a statement by our partner in this research project, the Ministry of Forests, Fauna and Parks of Québec (MFFP): “[the agency] is interested in industrial performance criteria and will further analyze the possibility of integrating the proposed criteria into the upcoming revisions of its wood allocation process. The approach and tools presented by the research team might be very useful to this process. On the other hand, we believe that additional research needs to be done to select measurable performance criteria in order to limit subjectivity in the ranking of companies. Thus, we appreciate very much this collaboration and MFFP will take it into consideration in its process to establish a wood allocation methodology based on performance criteria.”

As future research avenues, we believe that Analytical Network Process (ANP), fuzzy-AHP, and Multi-Attribute-Utility-Theory (MAUT) methods could all be used to improve the robustness of the proposed tool. The right method depends on the needs and preferences of experts and decision-makers as well as the data available in practice. Finally, we believe that research efforts need to be devoted to the evolvement of mill performances over time, and efforts are needed to determine allocations over several time periods in a more dynamic way.

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Appendix: Species and qualities required for each mill

Mill	*Manufactured products*	*Species*	*Quality*
Mill 1	Rough lumber (dried), planed lumber (dried), chips, bark, shavings, sawdust	SPF	Saw log
Mill 2	Rough lumber (green and dried), square lumber (green), pallets, boxes, crates, surveying pickets, railway sleepers, chips, bark, shavings, sawdust	HRDW	Veneer log
			Saw log
Mill 3	Planed lumber (green), fences and barriers, chips, bark, shavings, sawdust, wood trellis	SPF	Saw log
Mill 4	Pressure-treated wood	SPF	Saw log
		POPL	Veneer log
			Saw log
			Pulp log
Mill 5	Shingles	THUJ	Saw log
Mill 6	Corrugated cardboard, paper	HRDW	Pulp log
Mill 7	Charcoal, charcoal granules, charcoal dust	HRDW	Pulp log
Mill 8	Planed lumber (green), chips, bark, shavings, sawdust	SPF	Saw log
Mill 9	Rough lumber (green and dried), square lumber (green), pallets, boxes, crates, surveying pickets, railway sleepers, chips, bark, sawdust	POPL	Veneer log
			Saw log
			Pulp log
Mill 10	Rough lumber (green), chips, bark, sawdust	SPF	Saw log
Mill 11	Shingles	THUJ	Saw log
Mill 12	Stud, bed components	SPF	Saw log
Mill 13	Rough lumber (green, dried), planed lumber (green, dried), chips, bark, shavings, sawdust	SPF	Saw log
Mill 14	Rough lumber (green), chips, bark, sawdust	SPF	Saw log
		POPL	Saw log
Mill 15	Pallets, boxes, crates	POPL	Veneer log
		POPL	Saw log
		POPL	Pulp log
Mill 16	Rough lumber (dried), planed lumber (green), chips, bark, shavings, sawdust	SPF	Saw log
Mill 17	Laminated rough particle board, laminated MDF Panels	HRDW	Pulp log
Mill 18	Door panels, plywood (components of windows and doors, folding doors, decorative shutters)	HRDW	Saw log
Mill 19	High yield pulps, paper, cartons, cover paper, toilet paper , paper towels	HRDW	Pulp log
Mill 20	Floor, rough lumber (green), ecological logs	HRDW	Veneer log
			Saw log