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Thème

Natural resources allocation mechanism based on Coalition configuration: Forest Supply Chain Analysis

Soutenue le : Devant le Jury composé de :

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A Yemma, Nadia ma femme, nos enfants Aghiles, Juba & Aris que dieu vous préserve...
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List of abreviations

GDP	Gross Domestic Product
CC	Coalition Configuration
CCV	Coalition Configuration Value
CS	Cost Savings
MNRF	Minitary of Natural Resources and Forestry
SPF	Spruce-Pine-Fir
THUJ	Thuja
POPL	Poplar
HRDW	Hardwoods
CGT	Cooperative Game Theory
TU	Transferable Utility
AHP	Analytic Hierarchy Process
GP	Goal Programming
FSC	Forest Stewardship Council
GRI	Global Reporting Initiative
LCV	Least Core Value
GP-CC	Goal Programming- Coalition Configuration Value based Model
GP-LC	Goal Programming- Least Core Value based Model

Contributions of the thesis

- Rahmoune, M., Radjef, M. S., Boukherroub, T., and Carvalho, M. A new integrated cooperative game and optimization model for the allocation of forest resources. European Journal of Operational Research, Elsevier (2024).
- Rahmoune, M., Radjef, M. S., Boukherroub, T., and Carvalho, M., A multi criteria-Choquet based forest resources-allocation mechanism, A. Brown Greer, C. Contardo, J.-M. Frayret, eds. Proceedings of the IISE Annual Conference & Expo 2024.
- Rahmoune, M., Radjef, M. S., Boukherroub, T., and Carvalho, M., A new integrated cooperative game and optimization model for the allocation of forest resources, Séminaire hébdomadaire du LaMOS, Mardi 16-04-2024.
- Rahmoune, M., Radjef, M. S., and Boukherroub, T., A cooperative game model for natural resource allocation: Canadian forest product case study, In 13ème Congrès International de Génie Industriel (CIGI) QUALITA conference 2019 .
- Rahmoune, M., Radjef, M. S., and Boukherroub, T. A cooperative game model for forest resource allocation, CORS (Canadian Operational Research Society) Saskatoon, May 27-29- 2019.
- Rahmoune, M., Radjef, M. S., and Boukherroub, T., Analysis of the Strategic and Dynamic Behavior of the Actors in a Supply Chain, Poster au Doctoriales en Recherche Opérationnelle, le 12 et 13 Décembre 2018.

" Win id ak yennan d acu id tafat in as d iγallen yedduklen."

- Amazigh proverb,

General introduction

The allocation of natural resources is a problem of prime importance, especially when the resources to allocate are public-owned and limited. This is the case of forest resources in Canada, where more than 90% of the forests are publicly owned and rigorously managed to ensure long-term sustainable industrial use [15a, 16]. The forest sector provides a wide range of benefits for the country. In addition to the rich wildlife and various outdoor activities in the forest, the wood industry contributed with more than 14.5 billion dollars to Canada's real gross domestic product (GDP) [60]. It represents about 80% of the added value of the forest sector in the province of Quebec [53]. Since these resources are limited, mills compete fiercely for them.

Due to the public awareness of sustainability, among others, the Canadian government is willing to integrate economic, environmental, and social considerations into all aspects of forest resource management [15]. This applies to the allocation process of forest resources to industrial users (i.e., the beneficiaries are mainly mills). In the literature addressing this problem, the dynamics of the interactions among the mills, which influence the system as a whole, has not been considered in the allocation process. The synergy that leads to local and regional benefits thanks to collaboration is an important factor to consider in the allocation process because it is a driver of global welfare and global performance. For instance, collaboration can lead to significant reductions in costs (ranging from 4% to 46%) and CO_2 emissions [73a, 27]. This fact matters to the government and all the parties involved. Therefore, combining all of these aspects and objectives, which can sometimes seem contradictory, increases the complexity of the forest resource allocation problem.

We focus on a regional case study in the province of Quebec (Canada) where the specifics (e.g. manufactured products and quantity of wood needed) of the competing mills are taken into account in addition to their sustainability performance and their collaboration effort. In this region, we observed that for each operation of the upstream supply chain, which are harvesting, road construction/upgrading and transportation, coalitions of collaborating mills are formed, and each mill can belong to multiple coalitions at the same time. This means that the coalitions overlap which is known in the cooperative game literature as *coalition configuration* (CC) [4]. This is a generalization of the *coalition structure* concept [12] and the corresponding solution concept is known as *coalition configuration value* (CC value) [4], which is a generalization of the *Shapley value* [76]. We use the CC value to evaluate the contribution of each mill to the collaboration benefits.

This approach proposed in this study addresses the question of how to allocate public-owned forest resources to different beneficiary mills. Our first goal is to design a cooperative game models to capture the collaboration benefits and measure the contributions of each mill to the cost savings (CS). In addition, mills make individual efforts for the economic, environmental and social development and they may not collaborate with other mills for practical reasons. Therefore, both collaborative and individual sustainability efforts should be rewarded. Disregarding all these elements can result in unfair allocations and losses in terms of potential economic, environmental and social benefits. We, therefore, formulate a multi-objective optimization model encompassing these collaborative and individual elements in order to determine the volumes of the resources to allocate to each mill. Our approach is consistent with one of the oldest and most prominent theory about equity principle in its modern rendition [86a, 56] which states that "Equals should be treated equally, and unequals unequally, in proportion to the relevant similarities and differences "(Nicomachean Ethics of Aristot)[56].

Our study's distinctive feature is that the mathematical modeling is driven by real issues. It contributes to the literature on the resources allocation problem by considering simultaneously, collaboration and the individual sustainability performances of the beneficiaries in the allocation process. We provide a clear and practical answers to the problem of forest resources allocation when considering its main challenges. In fact, we formulate two methods. The second method is complementary to the first one. In the first, a bi-objective model is proposed: the first object concerns the collaborative efforts (CS), the second objective considers the individual aggregated performances. The second method is based on multi-criteria decision theory. The criteria considered are: Collaborative efforts (CS), environmental, social, economic performances. We can assume that each criterion may influence the others. Thus, we say that these criteria are not interdependent and there are interactions among them. To take into account the interaction phenomena, we aggregate the four criteria with Choquet Integral (CI) [20]. This mathematical tool enable us to take into account interactions among criteria and aggregate them into one evaluation of each player (Mill) based on which the allocation of the resources is proportional to this CI evaluation.

Thesis position and contribution: Globally, the problem we face here in this research is the efficient, sustainable and equitable allocation of public owned forest resources. In view of the literature on natural resources allocation problem (Section 1.3) in one side, and the real context description (Section 1.2) in the other side, our research matches well the research directions considering collaboration among the actors based on cooperative game theoretical solution concepts. It also covers multi-criteria aspects and optimization techniques. Therefore, our research contributes to the literature on natural resources allocation by:

- Considering collaboration benefits in the natural resources allocation problem. To the best of our knowledge, it is the first time that both collaborative and individual sustainability performances have been taken into account in a natural resources allocation problem;
- Unlike other studies, which consider collaboration regarding a single forestry operation, we consider it in regard to three different operations while taking into account the existence of overlapping coalitions,
- This is also the first time that the CC value, which is a generalization of the *Shapley value* [76], is applied to a real-world resource allocation problem. Moreover, we proposed a methodology for estimating the CC value based on the data collected,
- To the best of our knowledge, it is the first time that the coalitional stability is considered in a real resource allocation problem.
- This is the first time an aggregation function, whose aim is to capture the criteria on which the mills are evaluated, considers the interactions among these criteria in a resource allocation problem. This aggregation function is the Choquet Integral [20].

This thesis begins by this general introduction which sets the framework of this work and presents a first explanation of the research challenges, background and objectives. The rest of this document consists of four chapters organized as follows:

The first chapter is devoted to a more detailed description of the case study. Starting with some features of the region of Québec. After that, we will describe the forest operations under consideration. A section of this chapter is devoted to a detailed review of the most recent scientific literature on our subject.

In the second chapter, we describe the cooperative game formulation and the mathematical background needed to capture all the characteristics of the problem and which serve the approach we are developing.

The third chapter is dedicated to a detailed description of the methodology we adopted to address the problem. It includes two complementary allocation methods. The first proposes an allocation proportional to the collaborative efforts of the mills and their individual performance in relation to the objectives of sustainable development. According to this method, the two main criteria are considered separately. In the second method, the allocation is made proportional to the aggregation of the two main previous criteria (collaboration and sustainable performance) into a single performance evaluation of each mill.

In the fourth chapter, the results of computational experiments are presented and discussed. We end with a general conclusion that introduces future avenues of research.

1 Context description

THIS chapter draws the concrete and in-depth characteristics of the public-owned natural resource allocation problem that we face in a region of Québec in Canada. The aim is to grasp the issues at stake and illustrate the interactions between stakeholders.

In the first section, we present the regional context of the Québec region and illustrate the different challenges facing the government of this province. The second section describes the upstream forest supply chain. Three important forest operations are concerned: Harvesting, Road construction, upgrading and transportation. Collaboration between mills in these operations is highlighted as well as the importance of its consideration in the problem we are addressing. The recent academic literature on resource allocation problems is reviewed in the following section.

1.1 Regional context

In the province of Québec, forests cover an area of more than $900,000\ km^2$ which is 52% of its total area. From this area, 92% is public-owned and is under the responsibility of the government, i.e. the Ministry of Natural Resources and Forestry (MNRF) [53].

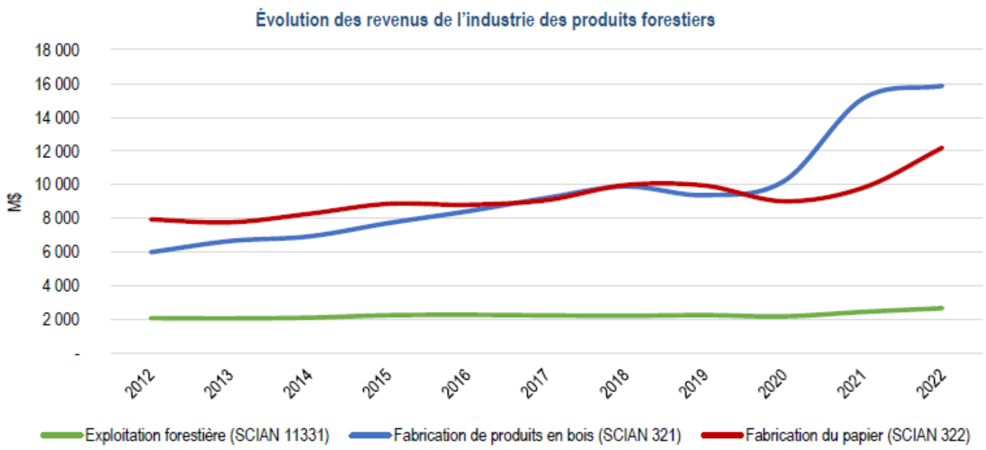


Figure 1.1 – *Evolution of the revenue of the forest industry in Québec.(Source :[79])*

As a collective wealth, the government considers that public forests preservation as at the heart of the population's concerns [52]. The forest in Canada, in general, and the province of Québec in particular offers rich biodiversity and various ecosystem services, wide life habitat, etc. It also provides recreation activities (outdoor activities, hunting, etc.). The MNRF has adopted sustainable forest management to maintain the long-term health of forest ecosystems. This is to ensure the availability of the resources in the future, and continue to provide current and future generations with environmental, economic and social benefits [52].

The forest industry is an important contributor to the Canadian economy. Indeed, we can observe the evolution of the revenue of the forest industry in Québec in Figure 1.1. In addition to these economic aspects, other environmental and social issues (clear-cutting, wildlife habitat destruction, First Nations right, etc) matter for everyone.

The wood is allocated to transforming companies through a supply and forest management agreement which gives the mills (license owner) the right (cutting right) to harvest in a specific region in Québec an indicated volume [15]. In the last years, the allocation problem became more challenging, because the government has reduced the maximum allowable volumes to 75% of the previous volumes. The remaining portion is put up for auction to open up new markets to competitors, permit the creation of fresh business models, and encourage the emergence of innovative products and solutions that benefit the environment, society, and economy. The current allocation approach is based on historical considerations which might be perceived as unfair by the stakeholders [15]. Therefore, the government seeks an efficient and sustainable allocation process ensuring equity among forest companies and maximizing the economic, environmental and social welfare.

In this study, we consider a set of 16 mills (license owners) manufacturing various wood products such as lumber, paper, etc., from different wood species available in the region under study in the province of Quebec. Each family of species has properties making them suitable for specific uses. We call these properties *qualities* [15]. These aspects are described in Table 1.1.

Table 1.1 – *Wood species and qualities available in the region under study [15]*

Species	**Qualities**		
	Saw log	**Vaneer log**	**Pulp log**
SPF (fir, spruce, pine, larch)	✓		
THUJ (thuja)	✓		
POPL (poplar)	✓	✓	✓
HRDW (maple, yellow birch, other hardwoods)	✓	✓	✓

The government of Quebec also seeks to improve the overall performance of its production system [46]. In the region under study, it is observed that mills collaborate in different forest operations to improve their performances. Economies built through collaboration improve the competitiveness of companies at the regional and international level.

However, the collaborative efforts are not rewarded in the current allocation process. Concretely, in our investigations, we found that these mills collaborate to reduce their operating costs in three operations of the upstream forest supply chain which are described in the section below.

1.2 Forest upstream operations

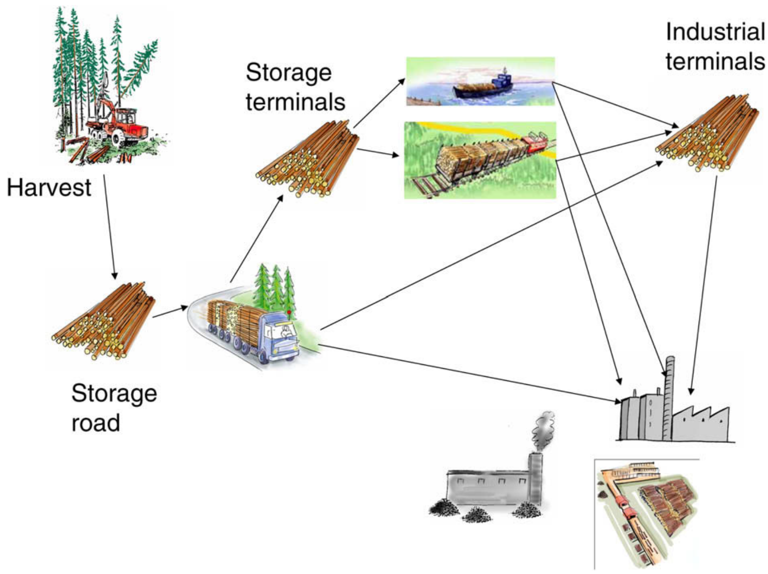


Figure 1.2 – *Wood Supply chain illustration (source [27])*

Figure 1.2 illustrates the wood supply chain. In the following, we focus on the upstream part: *Harvesting* of the wood, *road construction and upgrading* and *Transportation* of the wood to the transforming mills.

1.2.1 Harvesting operation

The harvesting operation involves two main steps *felling* and *forwarding*:

Felling is cutting down the trees into logs with various dimensions with respect to diameter and length. The machines used for this operation are called harvesters. A harvester in Figure 1.3 fells the trees and cut them into logs of various dimensions with respect to length and diameter.

Forwarding is picking up the logs distributed throughout the harvest areas and moving to storage locations adjacent to forest roads.

Figure 1.3 – *Harvesting operation (source:[25])*

1.2.2 Roads construction and upgrading operation

The forest roads must be upgraded because the industry is highly dependent on an efficient road network, since all the logs are transported some distance by trucks. Accessibility to the logs (piles) becomes difficult due to variations of weather conditions during the year. Blocking forest roads leads to increasing costs. In Sweden, for example, it is estimated that about 6% of the total cost to deliver the wood are due to insufficient road accessibility [25].

Figure 1.4 – *Road construction and upgrading operation (source:[25])*

1.2.3 Transportation operation

The industries are dependent on continuous deliveries throughout the year, whatever the conditions. Thus, transportation planning is integrated with forest management on time horizon of several years [25]. It begins at the harvesting or storage areas accessible by trucks, where the logs are loaded and transported to the mills (sawmills, paper mills etc.) for transformation. In Sweden, the transportation cost corresponds to one third of the total raw material cost in the forest industry [27]. In forestry, several modes of transportation are used: truck, train and ship. It can be done in one step or more. Environmental concerns are increasingly important aspects in transportation due to fuel consumption and CO_2 emissions [73a, 27].

Figure 1.5 – *Transportation operation (source:[25])*

We observed in the region under study that some mills participate in more than one coalition within each of the three operations. For example, the mills form distinct coalitions to harvest all the wood volumes scattered in the region and some mills participate in more than one coalition. By doing this, collaborating mills make more interesting CS.

In the following section, we will discuss the scientific literature about the resources allocation, especially natural ones, in the collaborative context. The focus will be on forest resources and also on collaboration where coalitions overlap.

1.3 Literature review

In general terms, the allocation problem is encountered when a bundle of a common and limited resource must be distributed among a set of agents. There are many studies devoted to this problem in the literature. Our review begins by a short illustration of applications to different resources, with more details on natural ones. Afterward, specific studies reporting on forest resources allocation are presented. In this setting, collaboration among agents is discussed.

The allocation problem applies to different resources. For instance, allocating energy [75], carbon emissions [87], telecommunication [2a, 88a, 26] and health resources [50a, 17a, 43a, 82]. Concerning natural resources, studies on water and hydrological resources are particularly abundant. This can be explained by the fact that it is a vital resource around which there might be many conflicts, as investigated in research [72a, 51a, 47a, 45a, 78a, 71a, 54a, 37a, 1a, 81a, 41]. In those studies, multi-criteria decision supports, optimization techniques and non-cooperative game theory (non-CGT) based approaches are used. The classic solution concepts of CGT, that do not consider overlapping coalitions, have been applied for water, grazing rights and fisheries management in [23a, 64a, 84].

Concerning forest resources, Boukherroub et al. [15a, 16] discuss the importance of the allocation process for sustainability integration in forestry supply chains. Real cases of forest resources allocation and planning are studied in [69a, 48a, 62a, 14a, 61a, 15a, 55]. In those studies, multi-criteria decision and optimization techniques are used. Collaboration is considered for forest management and product sharing as a bargaining game between the government and the local community of Bengal (India) by the study [36]. [66a, 67a, 68] proposed a resource allocation model based on the Shapley value. More recently [57] considered the problem of seed allocation in a collaborative reforestation value chain based on multi-objective models.

Collaboration, which assumes the formation of coalitions of agents to promote synergies, is often captured by CGT. For example, coalition formation in forestry transportation planning and cost allocation is studied based on CGT in [27a, 9a, 35a, 34a, 13]. Lehoux et al. [38] designed a coordination mechanisms for mills in a forest supply chain based on CGT solution concepts to achieve a long term profitability.

The aforementioned studies are based on the concept of *coalition structure* which is a partition of disjoint set of agents. However, in the real world, agents might have preferences or restrictions regarding the participants with whom they collaborate. In some situations, the coalitions overlap, i.e., the same company can be part of different coalitions at the same time, as pointed out by [12]. This situation is observed across many real-life problems, including our case study, where mills participate in more than one coalition for each operation in the forest supply chain. The relatively recent concept describing this situation is *coalition configuration* (CC) [77a, 4a, 5a, 70a, 69]. The authors of [32a, 33] studied the collaborative transportation problem in forestry within the context of overlapping coalitions, where integer programming models were used to identify the coalitions that minimize the total cost. A more recent research [46] presented a review on overlapping coalitions in the game theory literature. In this study, the authors emphasize on the formation of overlapping coalitions or on the best way to form them which is known as the problem of overlapping coalitions generation. They are rather new in the CGT literature. The few studies that deal with them use optimization techniques and focus on coalition formation. In the context of forest supply chains, the only operation studied while taking into account overlapping coalitions, is transportation operation. Moreover, there are even fewer studies that use the adapted CC value solution concept developed in [4a, 5a, 6a, 3] to evaluate the agent's contribution to collaboration.

According to the findings of this review, the CC value has not been used in any real-word situation, particularly in resources allocation problem. Furthermore, we have not found a study that has addressed collaboration in more than one forestry operation, especially when coalitions overlap. The collaboration is an important factor to consider in the allocation process because it is a driver of global performance. For instance, it can lead to significant reductions in costs (ranging from 4% to 46%) and carbon emissions [73a, 27]. These aspects matter for the government and forest companies, but makes the forest resources allocation problem more complex.

Conclusion of the chapter

In this chapter, we have presented the context of our research in the province of Québec and the three operations of the forest supply chain involved in our study, where mills cooperate to be more efficient. We then carried out an in-depth review of the literature to situate our problem in the scientific literature. The aim is to characterize and refine the problem defined before. In the next chapter, we introduce the mathematical background necessary to capture all the features of the problem described above.

2 Theoretical background and game model formulation

Since the middle of the twentieth century, principles, concepts, and methodologies originating in game theory have been successfully applied to such diverse fields as economics, politics, evolutionary biology, computer sciences, social psychology, law, epistemology and ethics, providing analytical, insightful ideas and explanations to various important problems in each of these fields. Particularly, the significant role of game theory in social sciences has been recognized by the award of the Nobel Prize for Economics to game theorists in many occasions (Example: Shapley Nobel Prize [59]).

The compelling reason for the application of game theory to natural resource problems in general and in our case particularly is that these problems stem from interdependence among agents, through their interrelated actions and strategies. The public good aspects of natural resources on local or global scales, and the externalities associated with them, make their management challenging.
Sustainable management call for control mechanisms designed to induce collective actions and cooperation among stakeholders. Therefore, thanks to the axiomatic construction of the solution concepts induced by cooperative game theory, an equitable treatment of the player (mills in our case) is guaranteed. This is in addition to an efficient use of the resource.

This chapter introduces the mathematical background necessary to understand our approach. The focus is solely on the cooperative game theory tools that we have used or mentioned in our research. We begin by giving the preliminaries for setting the formal language and defining the game. The second section is devoted to the construction of the characteristic function of the game. This is important because it captures the essential part of the game. Next, we give the algorithm that calculates the value of the game model. After that, we present some other solution concepts existing in cooperative game literature. Finally, we present the multi-criteria aspect and the aggregation function used to capture the dimensions of the sustainable development principles and collaborative efforts.

2.1 Preliminaries

In many situations, agents prefer or need to cooperate together than with others. As Aumann and Myerson (1988)[12] point out the case of Syria and Israel having diplomatic relations with USA but not with each other. An other example is the European Union where countries may be in more than one coalition depending on the issue at stake. It is the reason why, we assume players can form coalitions that are not mutually exclusive in order, for example, to attain better positions. As mentioned in the above sections, this situation is observed with the mills transforming the wood resource performing in Quebec (Canada) which is our case study.

In the classical cooperative game theory, the basic analysis of the coalition formation dynamics is provided by *coalition structure*. It's defined as a partition of the individual set into disjoint coalitions. Formally, given a finite set $\mathcal{N}$ of players, a cooperative transferable utility game on $\mathcal{N}$ (or simply TU-game) is characterized by a mapping $v : \mathcal{P}(\mathcal{N}) \longrightarrow \mathbb{R}$, with $v(\emptyset) = 0$. We remember that a **coalition structure** of $\mathcal{N}$ is a family $\Delta = \{\xi_1, \xi_2, \ldots, \xi_k\}$ of coalitions of $\mathcal{N}$ such that $\cup_{j=1}^{k} \xi_j = \mathcal{N}$ and $\xi_i \cap \xi_j = \emptyset, \forall i, j \in \mathcal{N}, i \neq j$, i.e. a player can only belong to one coalition. Moreover, the main solution concepts of TU-game $(\mathcal{N}, v)$ are associated to coalition structure concept.

In this field, an important reference is [11]. Owen [63], proposed and characterized a modification of the Shapley value [76] presented below:

The Shapley Value: Let $(\mathcal{N}, v)$ be TU-game (N, v). For each player $i \in \mathcal{N}$

$$Sh_i(v) = \sum_{\substack{S \subseteq \mathcal{N}: \\ i \in S}} \left(\frac{(|S|-1)!(|\mathcal{N}|-|S|)!}{\mathcal{N}!} \times [v(S) - v(S \diagdown \{i\})]\right. \tag{2.1.1}$$

This value respects a set of well-defined properties or *axioms* that fully characterize it. This was seminally pursued by Shapley [76a, 59] in his ground-breaking contribution. Subsequently, he showed that this value satisfies the following axioms: *Efficiency (Pareto), Null-player, Symmetry, additivity.*

The authors of [4a, 5] consider the more general concept of *coalition configuration* (CC) to model situations in which players form coalitions not necessary disjoint whose union is the grand coalition. They generalize the Banzhaf value [39] below, with reference to the CC [5]:

The Banzhaf Value: For each player $i \in \mathcal{N}$

$$\beta_i(v) = \frac{1}{2^{|\mathcal{N}|-1}} \sum_{S \subset \mathcal{N}, i \notin S} [v(S \cup i) - v(S)] \tag{2.1.2}$$

The authors of [4a, 5] generalized the Owen value (and, therefore the Shapley value) with reference to the CC.

In the following, we present the cooperative game model developed to capture the features of our case study. Let $\mathcal{N}$ be the set of $n = |\mathcal{N}|$ mills involved in the operations of the upstream forest supply chains under study and which are the beneficiaries of the wood to be allocated. The three operations (o) are: harvesting (h), road construction and upgrading (r) and transportation (t). In CGT, $\mathcal{N}$ is the grand coalition and its elements are the players of the game. A CC is a collection of non-empty subsets of $\mathcal{N}$ such that their union gives $\mathcal{N}$ [4]. Let $\mathcal{P}(\mathcal{N})$ be the set of all subsets of $\mathcal{N}$, whose cardinality is $2^{|\mathcal{N}|}$.

Definition 2.1.1. *For each operation $o \in O = \{h, r, t\}$, a CC is a set of non-empty coalitions $\Theta_o = \{\beta_1, ..\beta_k.., \beta_m\}$ of the players in $\mathcal{N}$, such that $\beta_k \subseteq \mathcal{N}$, $\bigcup_k \beta_k = \mathcal{N}$ and $\Theta = \Theta_h \cup \Theta_r \cup \Theta_t$ the set of the CCs.*

For each mill $i \in \mathcal{N}$, we define $\Theta_o^i = \{\beta \in \Theta_o : i \in \beta\}$, i.e., the set of coalitions in Θ_o to which i belongs and $o \in O = \{h, r, t\}$. For each operation $o \in O$, depending on the number of mills (in this case $n = |\mathcal{N}|$) different possible coalitions could be formed in theory. The measure associated to each possible coalition is expressed by a characteristic function $\upsilon_o : \mathcal{P}(\mathcal{N}) \to \mathbb{R}$ such that $\upsilon_o(\emptyset) = 0$. Indeed, many studies consider $\upsilon_o(S)$ as the worth of the coalition S [58].

Let $\Gamma_o = \Gamma(\Theta, \upsilon_o)$ be a transferable utility cooperative game associated to the operation $o \in O$ with $\Theta = \Theta_h \cup \Theta_r \cup \Theta_t$. The characteristic function υ_o will be presented in the next subsection. For solving this game, we use the solution concept of CC value, verifying the axioms of efficiency, null player, linearity, anonymity, coalitional symmetry and merger presented below:

We denote $\boldsymbol{\Theta}^{\mathcal{N}}$ the set of all coalition configurations on $\mathcal{N}$ and $G^{\mathcal{N}}$ the space formed by all TU-games on $\mathcal{N}$ and we denote: $\boldsymbol{\Theta}^{\mathcal{N}} \times G^{\mathcal{N}} = \boldsymbol{\Theta} G^{\mathcal{N}}$. A(point map) solution on $\boldsymbol{\Theta} G^{\mathcal{N}}$ is a map Φ such that $\Phi(\Theta, \upsilon) \in \mathbb{R}^{|\mathcal{N}|}$ for each $(\Theta, \upsilon) \in \boldsymbol{\Theta} G^{\mathcal{N}}$.

[4] have introduced the concept of CC value that generalizes the coalition values of Banzhaf [40a, 63] and [76]. Like the Banzhaf and the Shapley value, the CC value measures the marginal contributions of each player. And like the Owen value, it takes into account the possibility that some players are more likely to act together than with others, with reference to overlapping coalitions (CC).

We aim to calculate the contribution of each mill $i \in \mathcal{N}$ to the cost savings (CS). To do this, we consider the CS games $\Gamma(\Theta, \upsilon_o)$ and the CC value Φ_i^o, of each mill $i \in \mathcal{N}$ and for each operation $o \in \{h, r, t\}$ is the following:

$$\Phi_i^o(\Theta, \upsilon_o) = \sum_{\beta_q \in \theta^i} \sum_{\substack{\eta \subseteq \theta: \\ \eta \cap \theta^i = \emptyset}} \sum_{\substack{S \subseteq \beta_q: \\ i \in S}} \frac{|\eta|!(|\mathcal{N}| - |\eta| - 1)!}{m!} \times \frac{(|S| - 1)!(|\beta_q| - |S|)!}{|\beta_q|!} \times \left(\upsilon_o(A_\eta \cup S) - \upsilon_o(A_\eta \cup (S \setminus \{i\}))\right), \quad (2.1.3)$$

where $A_\eta = \bigcup_{\beta_r \in \eta} \beta_r$.

Albizuri et al. [4] generalized the following axioms, characterizing the CC value (2.1.3):

Efficiency axiom: For each cooperative game $(\Theta, \upsilon) \in \mathbf{\Theta} G^{\mathcal{N}}$: $\sum_{i \in \mathcal{N}} \Phi_i(\Theta, \upsilon) = \upsilon(\mathcal{N})$.
This axiom of efficiency says that the sum of what each player will receive must be equal to what the grand coalition has produced.

Null Player Axiom: If $i \in \mathcal{N}$ is a null player or a dummy player in game $(\Theta, \upsilon) \in \mathbf{\Theta} G^{\mathcal{N}}$ then $\Phi_i(\Theta, \upsilon) = 0$.
This axiom says that i is a dummy player if the amount that i contributes to any coalition is zero.

Linearity Axiom: For each $(\Theta, \upsilon), (\Theta, \omega) \in \mathbf{\Theta} G^{\mathcal{N}}$ and λ, $\mu \in \mathbb{R}$, it holds $\Phi(\Theta, \lambda\upsilon + \mu\omega) = \lambda\Phi(\Theta, \upsilon) + \mu\Phi(\Theta, \omega)$.
This axiom allows for a linear combination of values from several games. It considers the value obtained as that of a more global game. This axiom is used in this study. Thanks to this axiom, we are able to group the values obtained in the games in three forest operations.

Anonymity Axiom: Let $(\Theta, \upsilon) \in \mathbf{\Theta} G^{\mathcal{N}}$. If π is a permutation of $\mathcal{N}$ such that $\pi(\beta_q) = \beta_q$ for every $\beta_q \in \Theta$, then for every $i \in \mathcal{N}$ it holds: $\Phi_i(\Theta, \pi\upsilon) = \Phi_{\pi(i)}(\Theta, \upsilon)$.
This axiom says the value of each player is indifferent to his position.

Coalitional symmetry axiom: Let $(\Theta, \upsilon) \in \mathbf{\Theta} G^{\mathcal{N}}$. If $\beta_p, \beta_q \in \Theta$ are such that for every $\zeta \subseteq \Theta \setminus \{\beta_p, \beta_p\}$ it holds $\upsilon(\beta_p \cup \bigcup_{\beta_r \in \zeta} \beta_r) = \upsilon(\beta_q \cup \bigcup_{\beta_r \in \zeta} \beta_r)$, then $\sum_{i \in \beta_p} \Phi_i(\Theta, \upsilon) = \sum_{i \in \beta_q} \Phi_i(\Theta, \upsilon)$.
If two coalitions β_p, β_q are interchangeable; they contribute with the same amount to other coalitions then the sum of the values of the players that make up the coalitions are the same.

Merger Axiom: The merger axiom characterizes the overlapping aspect of the CC value. It guarantees that when a player leaves and another player takes its place (as representative of the leaving player), the values remain the same for the other players. In this study, if a mill designates a representative in a coalition configuration with full authority, then the merger axiom states that even with the inclusion of a representative, the remaining mills' expectations in terms of cost savings in the various operations remain unchanged.

Theorem 1. *([4]) The coalition configuration value* $\Phi = (\Phi_1, .., \Phi_n)$ *is given by* (2.1.3). *The value* Φ *satisfies the axioms of Efficiency, Null Player, Linearity, Anonymity, Coalitional Symmetry and Merger.*

In the following section, we will present the characteristic function that capture the realities of the situation considered in this study.

2.2 Characteristic function estimation

Through interviews conducted with the mill representatives (details on the survey process are mentioned in the following chapter), the percentage of CS achieved by the existing coalitions (in Θ_o) are obtained for each operation $o \in \{h, r, t\}$. We denote this percentage by σ_o. To build the characteristic function of each game Γ_o, we need to associate a payoff to all possible coalitions (not only to existing ones). Moreover, singleton coalitions should not benefit from any CS. In reality, we do not have exact information on the payoff of all the possible coalitions. To overcome the limitation of data in the calculation of the CC value, an estimation of the characteristic function of the game is proposed for all possible coalitions $S \in \mathcal{P}(\mathcal{N})$.

Let C_o denote an approximation of the unitary operating cost ($\$/m^3$) corresponding to operation o. It depends on the operation type $o \in \{h, r, t\}$ and the wood species. However, the data show that the species type SPF (Table 1.1) represents more than 80% of all wood species present in the region of study. For this reason, the unitary operating cost associated with SPF species is used for all species and for all operation type $o \in \{h, r, t\}$. Consequently, we define the function $f_o(\beta, S)$ which is an approximation of the unitary CS achieved by a given coalition $S \in \mathcal{P}(\beta)$ for $\beta \in \Theta_o$.

Definition 2.2.1. *For each operation* $o \in \{h, r, t\}$, *the set function* $f_o : \Theta \times \mathcal{P}(\mathcal{N}) \longrightarrow \mathbb{R}$ *is defined as follows:*

$$f_o(\beta, S) = \begin{cases} \sigma_o \times \frac{|S|-1}{|\beta|-1} \times C_o & \textit{if } \beta \in \Theta_o,\ |\beta| > 1,\ \textit{and } S \in \mathcal{P}(\beta), |S| > 1; \\ \sigma_o \times C_o & \textit{if } \beta \in \Theta_o,\ |\beta| > 1 \textit{ and } S \in \mathcal{P}(\mathcal{N}) \textit{ such that } \beta \subseteq S; \\ 0 & \textit{if } \beta \in \Theta_o\ ,\ |\beta| > 1 \textit{ and } S \in \mathcal{P}(\mathcal{N}),\ |S| \leq 1; \\ 0 & \textit{if } \beta \in \Theta_o \textit{ with } |\beta| \leq 1 \textit{ or } \beta \notin \Theta_o,\ \textit{and } \forall S \in \mathcal{P}(\mathcal{N}). \end{cases}$$

Note that if $S = \beta$, then the maximum unitary CS is achieved: $f_o(\beta, \beta) = \sigma_o \times C_o$. Moreover, if S is a singleton coalition no CS is obtained: $f_o(\beta, \{i\}) = 0,\ \forall i \in \mathcal{N}$. When S is neither an existing coalition (β) nor a singleton i, two cases can occur: (1) if S is a subset of β, then the CS is increasing with the size of S (the more mills join the coalition, the higher the CS is); (2) if S contains β, then the CS is the maximum achieved by β, since the mills in $S\backslash\{\beta\}$ do not contribute to the collaboration.
In addition, f_o is monotone increasing when $\beta \in \Theta_o$, i.e., $f_o(\beta, X) \geq f_o(\beta, \acute{X})$, for $\acute{X} \subseteq X \subseteq \beta$.

Definition 2.2.2. *For $o \in \{h, r, t\}$, we define the characteristic function: $\upsilon_o : \mathcal{P}(\mathcal{N}) \to \mathbb{R}$, as follows:*

$$\upsilon_o(S) = \begin{cases} \lambda_o(S) \left[\sum\limits_{\substack{\beta\in\Theta_o: \\ S\subseteq\beta}} f_o(\beta, S) + \sum\limits_{\substack{\beta\in\Theta_o: \\ \beta\subset S}} f_o(\beta, \beta) \right] & \textit{if } |S| \geq 2 \textit{ and } \exists\ \beta \in \Theta_o : S \subseteq \beta \textit{ or } \beta \subset S, \\ 0, & \textit{otherwise.} \end{cases}$$

where

$$\lambda_o(S) = \begin{cases} \frac{1}{|\{\beta\in\Theta_o : S\subseteq\beta\}| + |\{\beta\in\Theta_o : \beta\subset S\}|}, & \textit{if } |S| \geq 2 \textit{ and } \exists \beta \in \Theta_o \textit{ such that } S \subseteq \beta \textit{ or } \beta \subset S, \\ 0, & \textit{otherwise.} \end{cases}$$

The characteristic function υ_o measures the average CS over the set functions f_o, achieved by each $S \in \mathcal{P}(\mathcal{N})$. This function is null, i.e., no savings are achieved, for empty or singleton coalitions.

2.3 Coalition configuration value calculation

For the calculation of the CC value $\Phi_i^o = \Phi_i(\Theta, \upsilon_o)$ of the game $\Gamma(\Theta, \upsilon_o)$, we use Algorithm 1 below. It measures the marginal contribution of each mill to the CS for each operation. It is denoted by Φ_i^o for the operation $o \in \{h, r, t\}$, for mill i and it is measured in ($\$/m^3$) since it is the CS of the mill i. Afterwards, for the calculation of the CC value of the game $\Gamma(\Theta, \upsilon)$ with $\upsilon = \mu_h \upsilon_h + \mu_r \upsilon_r + \mu_t \upsilon_t$, thanks to the linearity axiom of the CC value ([4]), we use the formula:

$$\Phi_i(\Theta, \mu_h\upsilon_h + \mu_r\upsilon_r + \mu_t\upsilon_t) = \mu_h\Phi_i(\Theta, \upsilon_h) + \mu_r\Phi_i(\Theta, \upsilon_r) + \mu_t\Phi_i(\Theta, \upsilon_t) \tag{2.3.1}$$

$\forall \mu_o \in [0,1], o \in O$ such that $\sum_{o\in O} \mu_o = 1, \forall i \in \mathcal{N}$. Formula (2.3.1) allows us to aggregate the three values in one overall measure.

Algorithm 1 Calculation of Φ_i, for $i \in \mathcal{N} of the$

Require:
The CC: Θ_o, $o \in O = \{h, r, t\}$.
f_o: function (Definition 2.2.1).
υ_o: characteristic function (Definition 2.2.2).
Ensure: Calculation of the CC value Φ_i^o for $i \in \mathcal{N}$.
For each $o \in O = \{h, r, t\}$ and $i \in \mathcal{N}$, **Compute**:

$$\Phi_i^o = \sum_{\beta_q \in \theta^i} \sum_{\substack{\eta \subseteq \theta: \\ \eta \cap \theta^i = \emptyset}} \sum_{\substack{S \subseteq \beta_q: \\ i \in S}} \frac{|\eta|!(|\mathcal{N}| - |\eta| - 1)!}{m!} \times \frac{(|S|-1)!(|\beta_q| - |S|)!}{|\beta_q|!} \times (\upsilon_o(A_\eta \cup S) - \upsilon_o(A_\eta \cup (S \setminus \{i\}))) \quad (2.3.2)$$

where $A_\eta = \bigcup_{\beta_r \in \eta} \beta_r$
For each $i \in \mathcal{N}$, **Compute**: Φ_i according to Equation (2.3.1).
return $\{\Phi_i\}_{i \in \mathcal{N}}$

To express the overall contribution of the CS of each mill as weight (which will be used in the goal programming model (3.1.3)), we normalize the obtained value. To do this, *share function concept* is used. It is an approach to efficiently (efficiency property) share the worth of the grand coalition.

Formally, it is a vector $\Psi(\Theta, \upsilon_o) \in \mathbb{R}^{|\mathcal{N}|}$ such that $\sum_{i\in\mathcal{N}} \Psi_i(\Theta, \upsilon_o) = 1$. This concept was introduced by [83]. The authors of [7], applied this concept for games with a CC. The CC value-share function assigns to every player in the game its share-part according to the CC value. The main advantage, besides the fact that a share function respects efficiency, is that its use has no impact on the properties and axioms verified by the original values. Thus, we can replace Φ_i^o by Ψ_i^o(and Φ_i by Ψ_i) according to (2.3.3).

$$\Psi_i^o = \Psi_i(\Theta, \upsilon_o) = \frac{\Phi_i(\Theta, \upsilon_o)}{\sum_{i\in\mathcal{N}} \Phi_i(\Theta, \upsilon_o)}, \forall i \in \mathcal{N}, \forall \text{o} \in \text{O}. \quad (2.3.3)$$

2.4 Other solution concepts

We remain that cooperative game theory focuses on how to allocate gains (costs, costs savings,...) that are collectively obtained by a group of cooperating agents in a "desirable" way. Such ways are called "solution concepts". Different notions of desirable allocations properties lead to different solutions concepts. One of the most prominent one is the

Core. Suppose $x \in \mathbb{R}^{|\mathcal{N}|}$ is the allocation vector. The core of a CG $(\mathcal{N}, \upsilon)$ is the set of all allocation x such that:

$$\sum_{i \in \mathcal{N}} x_i = \upsilon(\mathcal{N}) \qquad ; \tag{2.4.1a}$$

$$\sum_{i \in \mathcal{S}} x_i \leq \upsilon(\mathcal{S}) \qquad \forall S \subseteq \mathcal{N} \tag{2.4.1b}$$

The condition 2.4.1a requires that the allocation in the core is *efficient*: the total amount of the gain is allocated to all players. The second condition guarantee that an allocation in the core is "subgroup rational" or *"stable"*: no subset of players, or coalitions, would be better off by abandoning the rest of the players and acting on its on. In other words, the core of a cooperative game is the set of all efficient and stable allocations.

For many games, the core may be empty. An other solution concept exists, initially proposed by Shapley and Shubik [28] and later named by Maschler et al. [49]. It is called *Least core* or *Least core value* (LCV) .

The Least core is formally defined for $\epsilon \in (-\infty, +\infty)$ by:

$$\zeta(\epsilon) = \left\{ x \in \mathbb{R}^{|\mathcal{N}|} : \upsilon(S) - \sum_{i \in S} x_i \leq \epsilon, \forall S \subseteq \mathcal{N}, \right\} \tag{2.4.2}$$

Below is the linear program calculating the least core value defined in (2.4.2).

$$\min \quad \epsilon \tag{2.4.3a}$$

$$s.t: \ \sum_{i \in \mathcal{N}} x_i = \upsilon(\mathcal{N}); \ \sum_{i \in \mathcal{S}} x_i - \upsilon(\mathcal{S}) \geq -\epsilon, \quad \forall S \subseteq \mathcal{N} \tag{2.4.3b}$$

$$\epsilon \in \mathbb{R} \ , x_i \geq 0, \qquad \forall i \in \mathcal{N}, \tag{2.4.3c}$$

The Least core (LCV) has several interesting economic interpretations. One of them is that the LCV minimizes the maximum dissatisfaction of any coalition. Other solution concepts exist in the literature, reader can see [65a, 28].

We note that when the core is not empty the Shapley value belongs to the core of the game $(\mathcal{N}, \upsilon)$.

2.5 Multi-criteria aggregation

Multicriteria Decision Aid (MCDA) aims to model the preferences of a decision maker (DM) over alternatives described by several criteria. Otherwise, the issue is to be able to analyze and explain a numerical model obtained by eliciting preferences of the DM. An issue of considerable interest in many areas is the aggregation. It refers to the process of combining several numerical values into a single one, so that the final result of aggregation takes into account, in a given manner, all the individual values. Classical aggregating operators are proposed: (weighted) arithmetic mean, geometric mean, median and many others. However, since these operators cannot model in any understandable way an interaction among criteria [44], they can only be used in the presence of independent criteria. They are not appropriate for aggregation of interacting criteria.

In the forest decision literature, multi-criteria decision making approach has been used to address a wide range of problems [22]. However, few studies considered multiple criteria in the forest resources allocation problem. Especially from, a sustainability point of view. As has been done in [15], the framework of this research also integrates the three dimensions of the sustainability developments: Economics, Social and Environment.
The economic criterion traduces the impact of the industrial activities on the local economy in terms of value-adding products/service diversification and benefits for locally based suppliers and industries. The environmental criterion reflects the impact of activities on the protection of the biodiversity, species at risk, and the ecosystem. The social criterion traduces the impact of the activities on the diversity/ equal opportunities and work conditions and engagement with First Nations and local communities.

By simply looking at this criteria, we can see that certain economically efficient measures have a direct impact on the environment, for example by affecting the ecosystem. This impact can be positive or negative. The same can be seen when complying with environmentally friendly or socially friendly measures. This mutual influence between criteria expresses what we call the interaction between criteria.

The problem of aggregating criteria to form a global utility function is of considerable importance in many disciplines. Here, we propose to use the Choquet Integral (CI) operator with a Fuzzy Measure that can capture interactions or synergy between criteria. It enlightens the link between multi-criteria decision making and cooperative game theory [44]. This is used here to have a unique value that takes into account all the criteria described above for each mill. Further on, the allocation of resources will be proportionally to this value. Below, we present an example by [44] to explain what we mean:

Example: *A university ranks applicants for postgraduate studies in management according to their marks in mathematics, statistics, and languages. Candidates who are good at mathematics are well known to be more likely good at statistics. This means that for students who are good at mathematics, the university prefers a student who is good at languages to one who is good at statistics, while for students who are weak in mathematics, a student who is good at statistics is preferred to a student who is good at languages. The information are presented in Table 2.1*: Consequently, we can say that in the situation described

Table 2.1 – *Candidate scores*

Candidates	**Mathematics**	**Statistics**	**Language skills**
E_1	40	90	60
E_2	40	60	90
E_3	80	90	60
E_4	80	60	90

in Table 2.1, candidate E_1 is preferred to candidate E_2, and candidate E_4 is preferred to candidate E_3. No system of weights can model the university's preferences over the set of candidates.

Let us assume the existence of such a weight system: We note ω_M the weight of **mathematics**, ω_S the weight of **statistics**, ω_L the weight of **language skills**, $\omega_M \geq 0$, $\omega_S \geq 0$, $\omega_L \geq 0$ and $\omega_M + \omega_S + \omega_L = 1$. Candidate E_1 is preferred to E_2:

$$40\omega_M + 90\omega_S + 60\omega_L > 40\omega_M + 60\omega_S + 90\omega_L,$$

so

$$\omega_S > \omega_L$$

Candidate E_4 is preferred to E_3:

$$80\omega_M + 60\omega_S + 90\omega_L > 80\omega_M + 90\omega_S + 60\omega_L,$$

so

$$\omega_S < \omega_L$$

$\omega_L < \omega_S$ and $\omega_L > \omega_S$ is impossible.

The impossibility of finding a system of weights representing the university's preferences is due to the fact that the relative importance of the two criteria, "statistics" and "language skills", depends on the scores obtained in "mathematics".

An interesting idea for modeling these situations is to assign weights not just to each criterion but also to each coalition of criteria. This comes down to defining a function of the set of possible coalitions between criteria. This function will be called, a *Fuzzy Measure* (called also a *Capacity*), on the set of criteria. This is the basis for calculating the Choquet Integral (CI). This is formally explained below.

Let $X = \{X_1, X_2, ..., X_k\}$ be a universe of elements (criteria).

Definition 2.5.1. *A fuzzy measure [80] μ on X is a function $\mu : \mathcal{P}(X) \to [0,1]$, satisfying the following axioms: 1) $\mu(\emptyset) = 0$ and 2) $A \subset B \subset X$ implies $\mu(A) \leq \mu(B)$. We will assume here $\mu(X) = 1$.*

In our context $\mu(A)$ represents the importance or the power of the coalition of criteria (group) A in the aggregation problem.

We can explain the interactions of criteria as made by M. Grabisch [29] in the following. Take two criteria $k, l \in X$ and $A \subseteq 2^{|X|}$:

- *Positive interaction* between k and l: the satisfaction of both criteria is much more valuable than the satisfaction of the separately:

$$\mu(A \cup \{k, l\}) - \mu(A) \geq (\mu(A \cup k) - \mu(A)) + (\mu(A \cup l) - \mu(A)),$$

  which can be written as:

$$\mu(A \cup \{k, l\}) - \mu(A \cup k) - \mu(A \cup l) + \mu(A) \geq 0$$

- *Negative interaction* between k and l: the satisfaction of both criteria is not that better than the satisfaction of one of them:

$$\mu(A \cup \{k, l\}) - \mu(A \cup k) - \mu(A \cup l) + \mu(A) \leq 0$$

- Case of equality: the added value by both criteria is exactly the sum of the individual added values *(independence between criteria)*.

Definition 2.5.2. *Let μ be a fuzzy measure on X. The discrete Choquet Integral of a function $g : X \to \mathbb{R}^+$ with respect to μ is defined by:*

$$\zeta_\mu(g) = \sum_{k=1}^{m} (g(X_{(k)}) - g(X_{(k-1)})\mu(A_{(k)}))$$

where $\cdot_{(k)}$ indicates that the indices have been permuted so that $0 \leq g(X_{(k)}) \leq ... \leq g(X_{(m)})$ and $A_{(k)} = \{X_{(k)}, ...X_{(m)}\}$ and $g(X_{(0)}) = 0$.

We have Choquet Integral as an aggregation function of multiple criteria due to its ability to take into account the interaction among the criteria and for other properties detailed in [31].

Returning the our university example. We note that "mathematics" and "statistics" have negative interaction, statistics and language have positive interaction (and similarly for mathematics and language):

Table 2.2 – *Fuzzy measure estimation*

A	**M**	**S**	**L**	**M,S**	**M,L**	**S,L**	**M,S,L**
$\mu(A)$	0.3	0.3	0.2	0.4	0.7	0.7	1

The results for each candidate are: $\zeta_\mu(E_1) = 63$, $\zeta_\mu(E_2) = 60$, $\zeta_\mu(E_3) = 71$, $\zeta_\mu(E_4) = 76$.

2.6 Conclusion of the chapter

In this chapter, we have defined the main concepts in relation to the cooperative game applied in this research. We have proposed a characteristic function that captures the reality of the situation studied. Finally, we introduced the aggregation function which allows us to consider the criteria with their interactions to have one value for each mill. The allocation of resources will be proportional to this value.

The following chapter provides details of the methodology used in this research.

3 Proposed methodology

In this chapter, we present the methodology adopted for designing our mechanism of forest resource allocation, which is cornerstone of our research. We propose a combination of cooperative game theory (CGT) and mathematical optimization. The idea behind it is to build an integrated approach that ensures more equity between mills and efficiency in resource management. It consists of two methods presented in two main sections. The first section presents the first fundamental allocation method developed in this research and describes all the steps that lead to the solution. The second section is devoted to the second allocation method and its steps.

In fact, the first method establishes the essential elements considered in this investigation. These are essentially: *Cooperation* (as a collective behavior), *sustainability performance* (as individual behavior) based on *sustainability* principles: economic, environmental, and social. We will end this section with a study of how players react to the allocation made by this method. More precisely, we will try to observe how inclined players are to stay in or leave their current coalitions in reaction to allocation made. This is more than a sensitivity analysis, because it does not just concern the parameters of the model but the structure of the system as a whole, i.e. the configuration of the coalitions.

In the second allocation method, it is based on multicriteria decision support. The aim is to have a single measure of mill performance obtained by a specific aggregation of different criteria. We consider four criteria: collaboration (contribution to cost savings), economic, environmental, and social performances. Therefore, we propose the use of the Choquet Integral as an aggregation function to have a single evaluation of each player (mill) while considering interactions and synergies among these criteria.

3.1 Allocation based on *Collaboration* and *Sustainability performance*

This method focuses on two separate objectives; one rewards collaborative efforts and the other rewards individual efforts to meet the principles of sustainable development. This method encompasses three phases as described in Figure 3.1: *1) Data gathering*, concerns the data used and different parties involved in this study, *2) Cooperative game model*, illustrates the collaborative aspects of this study *3) Goal programming model*, determines the volumes to allocate to each mill.

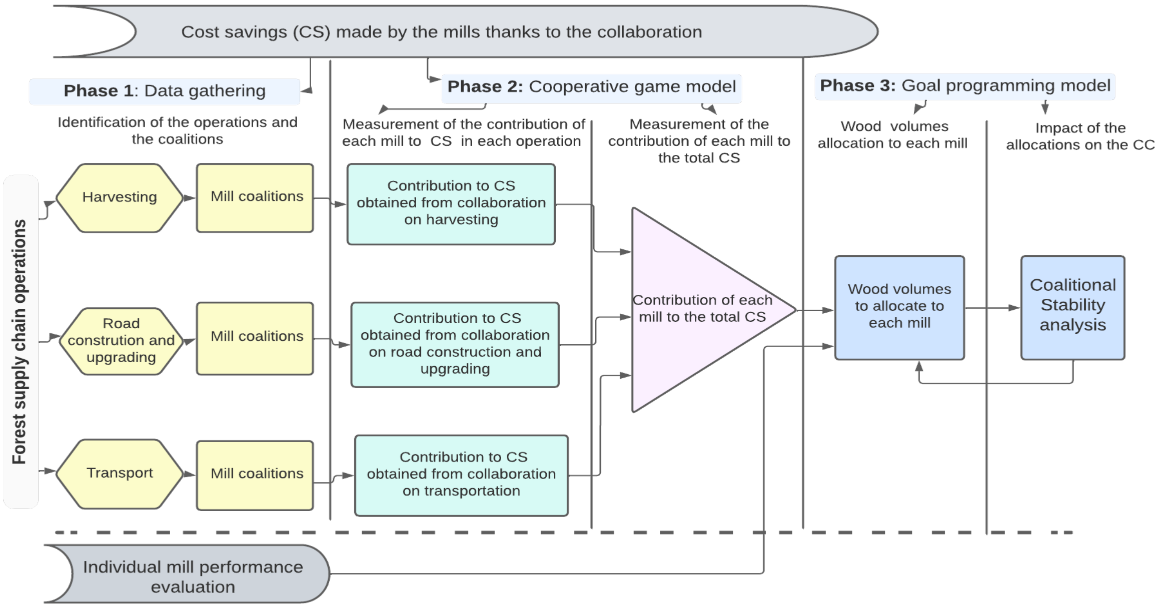


Figure 3.1 – *Proposed framework for the wood allocation problem (source:[70])*

3.1.1 Phase 1: Data gathering

Two types of data were collected: those concerning coalitions and collaborative efforts and those concerning individual mill sustainability performances.

3.1.1.1 Identification of the operations and the coalitions

We began by identifying the regional case study and collecting data on the mills involved in the allocation process and the current coalitions. To do this, we contacted all mills' representatives in the region under study in addition to governmental (MRNF) representatives at the provincial and regional level, as well as experts in the forestry sector. We contacted twenty persons in total and invited them to participate in the interviews conducted by the author. Therefore, we organized video conference meetings [1] of about 90 minutes. The interviews were held during the period of 31 August 2020 to 31 April 2021. The questionnaire covered the type of wood species and the qualities[2] manufactured by the mills, the transforming capacity, the volumes needed and the mills involved in collaboration in the forest supply chain operations. When collaboration occurs, we asked questions regarding the benefits and the CS achieved. These interviews allowed us to identify three operations

[1]Physical meetings were impossible due to COVID-19 pandemics.
[2]Wood qualities are properties making them suitable for specific use.

in the forest supply chain where collaborations arise as described in Section 1.2: *harvesting*, *road construction and upgrading* and *transportation*.
Let us label the mills as M_i for $i = 1, ..., 16$.

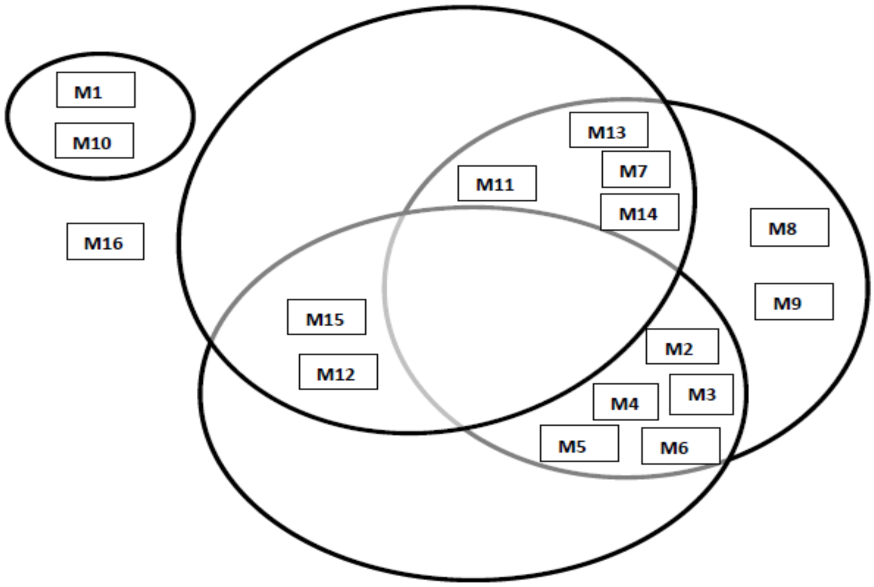


Figure 3.2 – *Existing coalitions for the harvesting operation*

Table 3.1 presents all the coalitions of mills observed in practice within the three operations. In the harvesting (h) operation, β_k^h represents the set of existent coalitions with

Table 3.1 – *Coalitions observed in the region of study*

Operation	**Coalitions**
Harvesting	$\beta_1^h = \{M_2, M_3, M_4, M_5, M_6, M_7, M_8, M_9, M_{11}, M_{13}, M_{14}\}$, $\beta_2^h = \{M_7, M_{11}, M_{12}, M_{13}, M_{14}, M_{15}\}$, $\beta_3^h = \{M_2, M_3, M_4, M_5, M_6, M_{12}, M_{15}\}$, $\beta_4^h = \{M_1, M_{10}\}$, $\beta_5^h = \{M_{16}\}$
Road construction and upgrading	$\beta_1^r = \{M_1, M_2, M_3, M_4, M_5, M_6, M_{10}, M_{12}, M_{15}, M_{16}\}$, $\beta_2^r = \{M_7, M_{11}, M_{12}, M_{13}, M_{14}, M_{15}\}$, $\beta_3^r = \{M_8\}$, $\beta_4^r = \{M_9\}$
Transportation	$\beta_1^t = \{M_2, M_3, M_4, M_5, M_6, M_7, M_8, M_9, M_{11}, M_{13}, M_{14}\}$, $\beta_2^t = \{M_2, M_3, M_4, M_5, M_6, M_{12}, M_{13}, M_{15}\}$, $\beta_3^t = \{M_1, M_{10}\}$, $\beta_4^t = \{M_{16}\}$

$k = 1, ..., 5$. We observe three overlapping coalitions: β_1^h, β_2^h and β_3^h . The CC corresponding to the harvesting operation is $\Theta_h = \{\beta_1^h, \beta_2^h, \beta_3^h, \beta_4^h, \beta_5^h\}$. For the operation of road construction and upgrading (r): $\Theta_r = \{\beta_1^r, \beta_2^r, \beta_3^r, \beta_4^r\}$; for the transportation operation (t): $\Theta_t = \{\beta_1^t, \beta_2^t, \beta_3^t, \beta_4^t\}$.

The estimation of CS resulting from collaboration of the mills is: $\sigma_h = 15\%$ for harvesting, $\sigma_r = 30\%$ for road construction and upgrading, and $\sigma_t = 15\%$ for transportation.

3.1.1.2 Individual mill performance evaluation

To consider the mills' individual performances, the data and results obtained in [15] (same regional case study) are used. The evaluation of the mills' performances was performed by two experts of the MRNF based on the sustainability criteria (*economy*, *environment* and *social*) by using the Group-AHP technique.

These individually sustainability performances are denoted by ω_i for each mill i in the model and expressed as normalized (%) weights (see Table 3.2). For more details, the reader can refer to [15].

3.1.2 Phase 2: Cooperative game model

CGT for overlapping coalitions is applied in two steps as follows.

Step 1: Measurement of the contribution of each mill to CS in each operation This step aims to measure the contribution of each mill to the CS for each operation. To do this, an estimation of the CS for any possible coalition is needed. The details of this estimation are presented in Subsection 2.2 and Algorithm 1.

Step 2: Measurement of the contribution of each mill to the total CS In this step, the results of the previous phase are aggregated in one normalized measure Ψ_i regarding its contribution to the total CS.

3.1.3 Phase 3a: Goal programming model

Goal Programming (GP) is an extension of linear programming to handle multiple objectives, introduced by [19]. This model is chosen because it is the most popular in the multi-objective programming field [8]. This modeling technique helps us to achieve equity between mills. This model is inspired from that proposed in [15].

There are many variants of GP in the literature. In this study, a weighted GP with two goals is considered. Goal 1 attempts to ensure that the allocations are proportional to the contributions of the mills to the CS achieved through the collaboration (Ψ_i). Goal 2 attempts to ensure that the allocations are proportional to their individual sustainability performances which are denoted by ω_i for $i \in \mathcal{N}$.
For both goals, the target is to have a perfect proportionality between the volumes of wood allocated and each mill's weight (individual sustainability performances (Goal 2) and CC value (Goal 1)). This is expressed in the Equations (3.1.1) and (3.1.2) below: X_{ei} and X_{ej} correspond to the volumes of wood specie e to allocate, respectively, to mill i and $j(\neq i)$.

The parameters Ψ_i, Ψ_j and ω_i, ω_j correspond to the weights of each mill associated to the normalized CC value and individual sustainability performance, respectively obtained by the mills.

$$\Psi_i \times X_{ej} - \Psi_j \times X_{ei} = 0, \quad \forall e \in E, \forall i, j \in \mathcal{N}, i \neq j. \tag{3.1.1}$$

$$\omega_i \times X_{ej} - \omega_j \times X_{ei} = 0, \quad \forall e \in E, \forall i, j \in \mathcal{N}, i \neq j. \tag{3.1.2}$$

However, achieving the targets perfectly is not always feasible. This is the reason why the deviation variables were introduced to represent, respectively, the deviations up (+) and down (-) from each one of the two goals. The two goals, in the model, are expressed by constraints. The objective function minimizes the sum of the positive and negative deviation variables from the ideal situation for the two goals. The relative importance of the goal can be expressed through weights (γ and $\bar{\gamma}$ in Equation (4.1.1)). For further details on GP, readers may refer to [74].

The decision variables and the parameters of the proposed model are presented in Table 3.2. The variables $\delta_{ije}^{(+)}$ and $\delta_{ije}^{(-)}$ represent, respectively, the deviations up (+) and down (-) from goal 1. In the same way, we define the variables $\tilde{\delta}_{ije}^{(+)}$ and $\tilde{\delta}_{ije}^{(-)}$ as the deviations up (+) and down (-) from goal 2.

The objective function (3.1.3) minimizes the sum of the positive and negative deviations from the ideal situation for the two goals.

$$\min \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{N}} \sum_{e \in E} \left(\left(\delta_{ije}^{(+)} + \delta_{ije}^{(-)} \right) + \left(\tilde{\delta}_{ije}^{(-)} + \tilde{\delta}_{ije}^{(+)} \right) \right) \tag{3.1.3}$$

Subject to the constraints below:
The set of constraints (3.1.4) and (3.1.5) represent the relation between the deviation variables and goal 1 and goal 2 , respectively.

$$\delta_{ije}^{(-)} - \delta_{ije}^{(+)} = \Psi_j \times X_{ei} - \Psi_i \times X_{ej}, \quad \forall e \in E, \ \forall i, j \in \mathcal{N}, i \neq j \tag{3.1.4}$$

$$\tilde{\delta}_{ije}^{(-)} - \tilde{\delta}_{ije}^{(+)} = \omega_j \times X_{ei} - \omega_i \times X_{ej}, \quad \forall e \in E, \ \forall i, j \in \mathcal{N}, i \neq j \tag{3.1.5}$$

The set of Constraints (3.1.6) states that the sum of the volumes of all qualities within that species e allocated to mill j should be equal to the volume of the specie e allocated

Table 3.2 – *Definitions of sets, decision variables and parameters of the mathematical model.*

Sets	
N_s	set of mills processing veneer log and/or saw log and pulp log qualities
N_p	set of mills processing only pulp log quality.
$\mathcal{N}$	set of all mills $\mathcal{N} = N_s \cup N_p$.
E	set of wood species: $E = \{SPF, THUJ, POPL, HRDW\}$
Q	set of qualities: $Q = \{SL^{spf}, VL^{popl}, PL^{popl}, SL^{popl}, VL^{hrdw}, SL^{hrdw}, PL^{hrdw}\}$
Q_e	set of qualities of species e: $Q_{POPL} = \{VL^{popl}, PL^{popl}, PL^{popl}\}$
Q_s	set of wood qualities allowable to N_s
Q_p	set of wood qualities allowable to N_p
Decision Variables	
X_{ej}	Volume of species e to allocate to *mill* (j) (m^3)
Y_{qj}	Volume of quality q to allocate to *mill* (j) (m^3)
X	$X = \{X_{e,j}\}_{j\in\mathcal{N}}^{e\in E}$ The set of the volumes of all species allocated to the mills by the model (3.1.3).
Y	$Y = \{Y_{q,j}\}_{j\in\mathcal{N}}^{q\in Q}$ The set of the volumes of all qualities allocated to the mills by the model (3.1.3).
$Z = (X, Y)$	The solution of the model (3.1.3).
$\delta_{ije}^{(+)}$	*Up or positive* deviation variable from the ideal proportionality between volumes of specie e allocated to mills i, j for goal 1.
$\delta_{ije}^{(-)}$	*Down or Negative* deviation variable from the ideal proportionality between volumes of specie e allocated to mills i, j for goal 1
$\tilde{\delta}_{ije}^{(+)}$	*Up or Positive* deviation variable from the ideal proportionality between volumes of specie e allocated to mills i, j for goal 2.
$\tilde{\delta}_{ije}^{(-)}$	*Down or Negative* deviation variable from the ideal proportionality between volumes of specie e allocated to mills i, j for goal 2.
Parameters	
A_q	Annual Allowable Cut for quality q, which is the total volume of quality $q \in Q$ available for allocation.
K_{ej}	Processing capacity of mill j for specie e.
$\underline{V}_{qj}$	Minimum volume of quality $q \in Q$ that should be allocated to j regardless of its performance.
ω_j	Sustainability performance of mill j
Φ_j	Contribution of mill j to the total CS, the CC value of player j.
Ψ_j	Contribution of mill j to the total CS (normalized value) which replace Φ_j.

to mill j.

$$X_{ej} = \sum_{q \in Q_e} Y_{qj}, \quad \forall e \in E, \quad \forall j \in \mathcal{N} \tag{3.1.6}$$

The set of Constraints (3.1.7) expresses that the total allowable volumes of a given quality q should be allocated to the mills.

$$\sum_{j \in \mathcal{N}} Y_{qj} = A_q, \quad \forall q \in Q \tag{3.1.7}$$

The set of Constraints (3.1.8) indicates that the wood volume allocated to mill j should be less or equal to its processing capacity.

$$X_{ej} \leq K_{ej}, \quad \forall e \in E, \forall j \in \mathcal{N} \tag{3.1.8}$$

The set of Constraints (3.1.9) states that the volumes allocated to the mills should be equal to or greater than a minimum volume.

$$Y_{qj} \geq \underline{V}_{qj}, \quad \forall q \in Q, \forall j \in \mathcal{N} \tag{3.1.9}$$

The set of Constraints (3.1.10) indicates that sawmills [3] should not be allocated more than 45% for the quality pulp log PL^{popl}.

$$Y_{VL^{popl}j} + Y_{SL^{popl}j} \geq 0.55 \times X_{poplj}, \quad \forall j \in N_s \tag{3.1.10}$$

The set of Constraints (3.1.11) and (3.1.12) states that sawmill processing HRDW should be allocated only veneer log and/or saw log qualities whereas pulp mills should be allocated only pulp log quality.

$$Y_{VL^{hrdw}j} + Y_{SL^{hrdw}j} = X_{hrdwj}, \quad \forall j \in N_s \tag{3.1.11}$$

$$Y_{VL^{hrdw}j} + Y_{SL^{hrdw}j} = 0, \quad \forall j \in N_p \tag{3.1.12}$$

Finally, all the decision variables should be continuous and positive as expressed by Con-

[3] Mills processing veneer log and/or saw log and pulp log qualities

straints (3.1.13) and (3.1.14).

$$\tilde{\delta}_{ije}^{(-)} \geq 0, \tilde{\delta}_{ije}^{(-)} \geq 0, \delta_{ije}^{(-)} \geq 0, \delta_{ije}^{(+)} \geq 0, \quad \forall e \in E, \forall i, j \in \mathcal{N}, i \neq j \tag{3.1.13}$$

$$Y_{qj} \geq 0, X_{ej} \geq 0, \quad \forall q \in Q, \forall e \in E, \forall j \in \mathcal{N}. \tag{3.1.14}$$

3.1.4 Phase 3b: Coalitional stability

The objective of this section is to examine whether these volumes allocated lead or not to changes in the CC structure. This leads us to the *coalitional stability* analysis of the CC. Most of the literature deals with this issue in the context of coalition formation game. However, in this case study, the CC is given "*exogenously*". We assume that the geographic location of harvesting operation is an essential factor in the coalition formation process of the current CC in addition to other factors such as complementarties between mills in terms of wood species required or qualities processed, as well as historical collaborations. Mills, as rational decision makers, form coalitions in order to maximize their benefits.
For the current CC, the weight related to the collaboration efforts of each mill Ψ_i is taken into account in the GP model (3.1.3) through the formulation of goal 1. Thus, any movement of a mill[4] from one coalition to another, will have an impact on the values of Ψ_i of goal 1 and therefore on the volumes allocated to the mills by the GP model (3.1.3). This characterizes the coalitional stability in the study. To define the concepts of stability of the CC, we need to introduce some notations: Let $Z(\Theta) = (X(\Theta), Y(\Theta))$ be the corresponding solution of the GP model (3.1.3) when the goal 1 is formulated with the CC value $\Psi(\Theta)$. Such that $X(\Theta) = \{X_{ei}\}_{i \in \mathcal{N}}^{e \in E}$ and $Y(\Theta) = \{Y_{qj}\}_{j \in \mathcal{N}}^{q \in Q}$. We will denote $\Pi_i = \Pi_i(Z(\Theta)) = \sum_{e \in E} X_{ei}(\Theta)$ the payoff of mill i, which is the volumes of wood allocated by the model (3.1.3) to mill i.

The coalitional stability studied here is based on *internal and external stability*. In other words, for each operation $o \in O$, and coalition $\beta \in \Theta_o$, no mill $i \in \beta$ would gain more by leaving the coalition *(internal stability)*. On the other hand, *external stability* means that for any mill $i \in \mathcal{N}$, which acts individually, either has no interest in joining any coalition $\beta \in \Theta_o$, or if it finds a coalition β, which will enable it to earn more by joining it, then there would exist in this coalition a mill $j \in \beta$ which would oppose i's entry, because the entry of i in β would reduce the payoff of j. In what follows, we will give the formal definitions of the internal and external stability of the CC: $\Theta = \Theta^h \cup \Theta^r \cup \Theta^t$ with respect to $Z(\Theta)$.

[4]Here, to simplify, we consider the movement of a single player/mill at a time.

Definition 3.1.1. ***Internal stability:*** *The CC* $\Theta = \Theta_h \cup \Theta_r \cup \Theta_t$ *is Internally Stable With Respect (SWR) to the solution* $Z(\Theta)$ *of the model (3.1.3) if* $\forall o \in O$, $\forall \beta \in \Theta_o$, *we have:*

$$\forall i \in \beta : \Pi_i(Z(\Theta)) \geq \Pi_i(Z(\bar{\Theta})), \tag{3.1.15}$$

where $\bar{\Theta} = (\Theta \setminus \Theta_o) \cup \bar{\Theta}_o$ *and* $\bar{\Theta}_o = (\Theta_o \setminus \beta) \cup (\beta \setminus i) \cup \{i\}$ *is the CC* Θ_o, *when the player* $i \in \beta \in \Theta_o$ *leaves the coalition* β *to act individually.*

Concerning the *external stability*, we will assume that each player of each coalition β of the CC Θ_o has "the veto" to oppose any player joining the coalition β, if his payoff decreases. This hypothesis is assumed in the "Exclusive Membership rule", where consent to the existing members is required for an outsider to join a coalition [85].

Definition 3.1.2. ***External stability:*** *The CC* $\Theta = \Theta_h \cup \Theta_r \cup \Theta_t$ *is externally SWR to the solution* $Z(\Theta)$ *of the model (3.1.3), if* $\forall o \in O$, $\forall \beta \in \Theta_o$, *we have either*

$$\begin{aligned}
&\forall i \notin \beta : && \Pi_i(Z(\Theta)) \geq \Pi_i(Z(\bar{\Theta})), && (3.1.16)\\
&\textit{else if there exists } i \in \beta \textit{ such that:} && \Pi_i(Z(\Theta)) < \Pi_i(Z(\bar{\Theta})), && (3.1.17)\\
&\textit{then, there exists at least one player } j \in \beta \textit{ for which } && \Pi_j(Z(\Theta)) > \Pi_j(Z(\bar{\Theta})), && (3.1.18)
\end{aligned}$$

where $\bar{\Theta} = (\Theta \setminus \Theta_o) \cup (\bar{\Theta}_o)$ *and* $\bar{\Theta}_o = (\Theta_o \setminus \{i\}) \cup (\beta \cup i)$.

Equation (3.1.16) expresses that i has no interest in joining β. But, if it earns more (Equation (3.1.17)), Equation (3.1.18) expresses that there is at least a player j whose payoff decreases which leads us to our hypothesis.

3.2 Allocation based on the aggregation of criteria by the Choquet Integral function

As mentioned before, in this method which is derived from the first one, the allocation is based on four criteria aggregated into a single one. The first three criteria are: *economic*, *environment* and *social aspects* which are consistent with the FSC (Forest Stewardship Council) and GRI (Global Reporting Initiative) standards [15]. The fourth criterion evaluates the mills on their *collaboration efforts* in an overlapping coalition context; see Figure (4.1) and [70]. The approach we propose, here, is designed to improve the global welfare and is based on the following steps:

3.2.1 Step 0: Criteria selection

Select the criteria on which the mills should be evaluated: economic (X_1=Ec), environmental (X_2=Env), social aspects (X_3=S) and the collaboration effort (X_4=CE): For each mill $i \in \{1, .., 16\}$: $X(i) = \{X_1(i), X_2(i), X_3(i), X_4(i)\}$. We simplify by noting: $X(i) = \{Ec(i), Env(i), S(i), CS(i)\}$. In other words, a mill is characterized by its performance following these four criteria.

3.2.2 Step 1: Mill evaluation

Evaluate each mill according to each selected criterion. Concerning the evaluation of the three sustainability criteria, two government experts assessed the performances of each mill by reference to standards such as: Forest Stewardship Council (FSC) and Global Reporting Initiative (GRI). For more details, the reader can refer to [15]. For the *collaboration effort* criterion, refer to the equations in Algorithm (1) and Appendix (2.4.2).

3.2.3 Step 2: Fuzzy measuring

Consider the set of all the criteria. We begin by giving a measure (fuzzy measure 2.5.1) $\mu(k)$ of the importance of each criterion k. For each possible group A of criteria, we give a measure of the importance of this group $\mu(A)$ in accordance with level of the interaction between its constituent criteria. We talk about positive interaction when $\sum_{k \in A} \mu(k) \leq \mu(A)$ and about negative interaction otherwise. This step, could be done based on the decision maker preferences, statistics or expert's estimations.

3.2.4 Step 3 Choquet aggregation

Calculate the aggregated performance of each mill according to the four criteria based on the Choquet Integral (see Definition 2.5.2).

3.2.5 Step 4: Wood allocation

Finally, we allocate the volumes of wood to each mill proportionally to its performance (aggregated value). In our case, we use the goal programming model developed initially by [15], with one goal. The changes only concern the objective function (Equation(3.2.1)) and the constraint that characterizes the goal in question, which is an allocation proportional to the aggregate performance of the mills (Constraint(3.2.2)). In this model: $\mathcal{N}$ is the set of the 16 mills; E the set of the wood species e: $E = \{SPF, THUJ, POPL, HRDW\}$; X_{ei} is the volume of species e to allocate to *mill* (i) (m^3); Ψ_i^{Choq} the aggregated performance of mill (i) based on Choquet Integral; $\delta_{ije}^{Choq(-)}$ and $\delta_{ije}^{Choq(+)}$ are respectively *negative* and *positive* deviation variables from the ideal proportionality between the volumes of species e allocated to mills i, in regards to mill j for our goal. The volumes allocated to mills processing SPF (fir, spruce, pine, larch) species are presented in Figure 4.11.

$$\min \quad \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{N}} \sum_{e \in E} \delta_{ije}^{Choq(+)} + \delta_{ije}^{Choq(-)} \tag{3.2.1}$$

$$s.t. \ \delta_{ije}^{Choq(-)} - \delta_{ije}^{Choq(+)} = \Psi_j^{Choq} \times X_{ei} - \Psi_i^{Choq} \times X_{ej}, \quad \forall e \in E, \ \forall i, j \in \mathcal{N}, i \neq j \tag{3.2.2}$$

3.3 Conclusion of the chapter

In this chapter, we present exhaustively the two resource allocation methods we propose in this thesis. In fact, the second is simply derived from the first. Both take a holistic view of player performance, considering collective (collaboration), individual and sustainable aspects. The allocation of the resource volumes must be proportional to these performances.

In the following chapter, we experiment the two methods.

4 Computational experiments and results

THIS chapter puts into practice all the aspects and tools developed and adapted by our approach. It describes step-by-step the process to be followed to obtain the allocations of the resources to the mills (players) according to the two methods described above.

4.1 Results of the allocation based on Collaboration and Sustainability performances

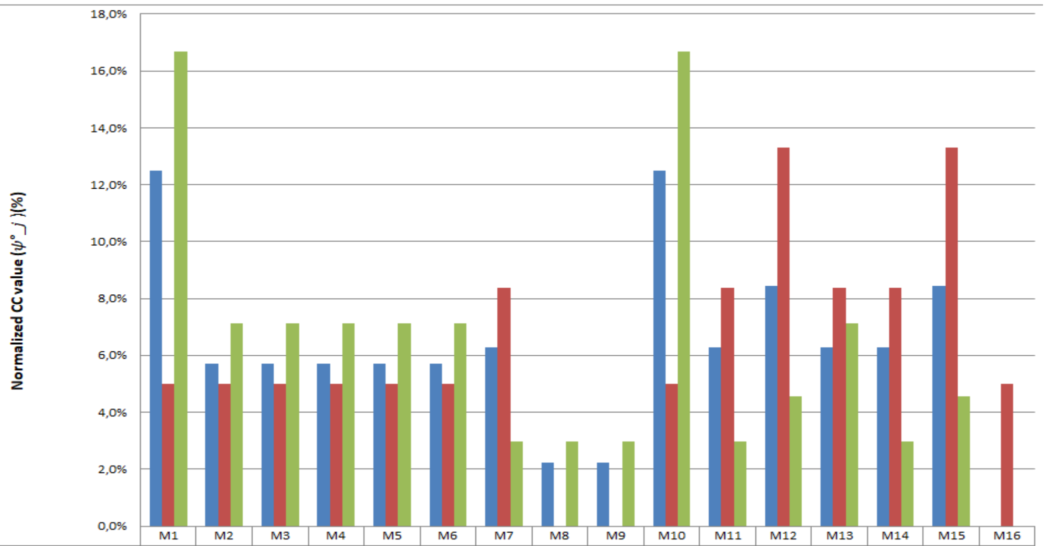
This section is divided into three subsections. The contributions of each mill to the CS are calculated in the first Subsection 4.1.1 which corresponds to *Phase 2* of the framework (see Figure (3.1)). In the second Subsection 4.1.2, the volumes to allocate to each mill (*Phase 3*) are determined. The last Subsection 4.1.3 presents a sensitivity analysis of the model and discusses the coalitional stability of the CC. A comparison of the CC value with an other CGT solution concept, witch is the *least core*, has been performed and the results are presented in Section 4.1.5.

4.1.1 Results of the cooperative game model

Step 1: Measurement of the contribution of each mill to CS in each operation: The calculation procedure described in Algorithm 1 is applied. By doing this, the CC value of each mill is applied. It is a measure of each mill's marginal contribution to the CS achieved at each operation considered in the upstream supply chain. The calculation was implemented in Python 3.7 and cvxpy which is an open source Python-embedded modeling language. The normalized CC values (Ψ_i^o) are presented in Figure (4.1):

Harvesting (h) : We observe that M_{16} does not participate in any coalition and therefore does not contribute to the CS (its value is zero). It is a *null player* in the sense of the axiom of the CC value (see Section 2.1). We observe that mills participating in more than one coalition get better values than the mills participating in one coalition only. For instance, M_8 and M_9 get lower values ($\Psi_8^h = \Psi_9^h = 2.2\%$) than $M_7, M_{11}, M_{13}, M_{14}$ get value (6.3%). The size of the coalitions is an important aspect mentioned in previous works that have studied collaboration in logistics [24a, 35a, 42]. In fact, this experiment shows that the contribution to the CS amount is affected by the size of the coalitions: the members of the coalition $\beta_4^h = \{M_1, M_{10}\}$ get higher values ($\Psi_1^h = \Psi_{10}^h = 12.5\%$) than coalitions β_1^h and β_2^h whose sizes are, respectively, 11 and 6.

Road construction and upgrading (r): Mills M_8 and M_9 are null players. Mills M_{12} and M_{15} belong to the intersection of overlapping coalitions and get the highest values



	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16
harvesting	12,5%	5,7%	5,7%	5,7%	5,7%	5,7%	6,3%	2,2%	2,2%	12,5%	6,3%	8,5%	6,3%	6,3%	8,5%	0,0%
road construction and upgtrading	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	8,4%	0,0%	0,0%	5,0%	8,4%	13,3%	8,4%	8,4%	13,3%	5,0%
transportation	16,7%	7,1%	7,1%	7,1%	7,1%	7,1%	3,0%	3,0%	3,0%	16,7%	3,0%	4,6%	7,1%	3,0%	4,6%	0,0%

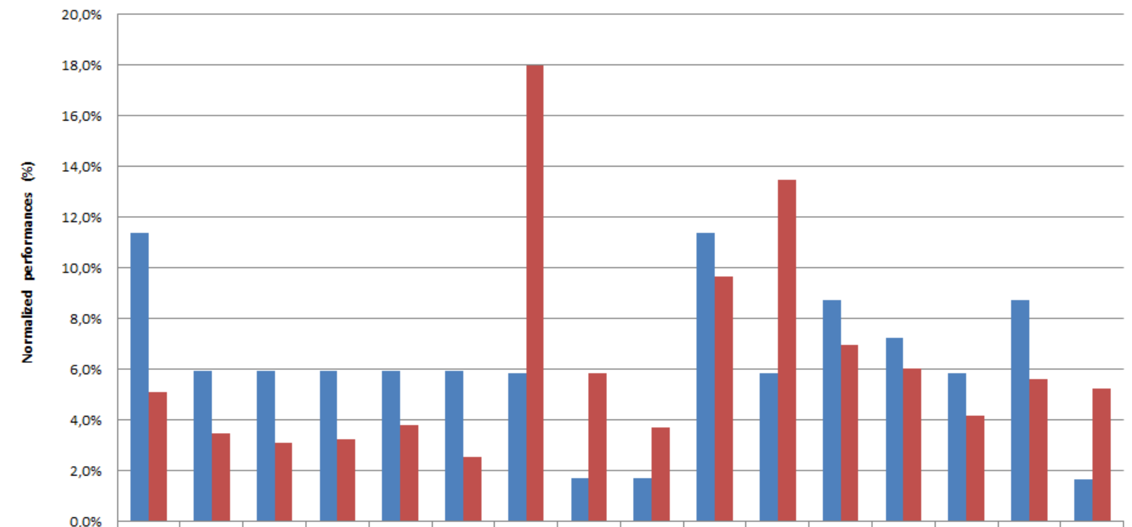
Figure 4.1 – *Contribution to CS obtained by the mills in harvesting, road construction/upgrading and transportation*

($\Psi^r_{12} = \Psi^r_{15} = 13.3\%$). As mentioned before, the size of the coalitions is important; mills belonging to coalition β^r_1 whose size is 10, get lower values (5%) than mills belonging to coalition β^r_2 whose size is 6 and the value of its members is 8.4%.

Transportation (t) : Mill M_{16} gets zero. When we consider the overlapping coalitions β^t_1 and β^t_2, the mills belonging to $\beta^t_1 \cap \beta^t_2$ get higher values (7.12%) than the other mills of these coalitions whose values are 4.5 % and 3%. Mills M_1 and M_{10} get better values because they collaborate in a small size coalition.

Three main observations could be highlighted : 1) non collaborating mills get zero, 2) mills in small coalitions get higher CC value than those in large coalitions, 3) mills belonging to more than one coalition get higher CC value than those in one coalition. These observations are consistent with the definition of the characteristic function of the cooperative game model (see Definitions: 2.2.1, 2.2.2 and Section 2.1).

Step 2: Measurement of the contribution of each mill to the total CS. As mentioned in Section 3.1.2, in this phase the contributions to the CS obtained by each mill in each operation are aggregated into one measure that represents each mill's contribution to the total CS (in all operations). This is obtained by using Equation (2.3.1). We chose to set the value of λ_1, λ_2 and λ_3, equal to $\frac{1}{3}$. This describes a situation where the three operations have the same importance. Figure (4.2) illustrates the results of the aggregation in this case. The case where the weights are not equal are discussed in the sensitivity analysis (Section 4.1.3).

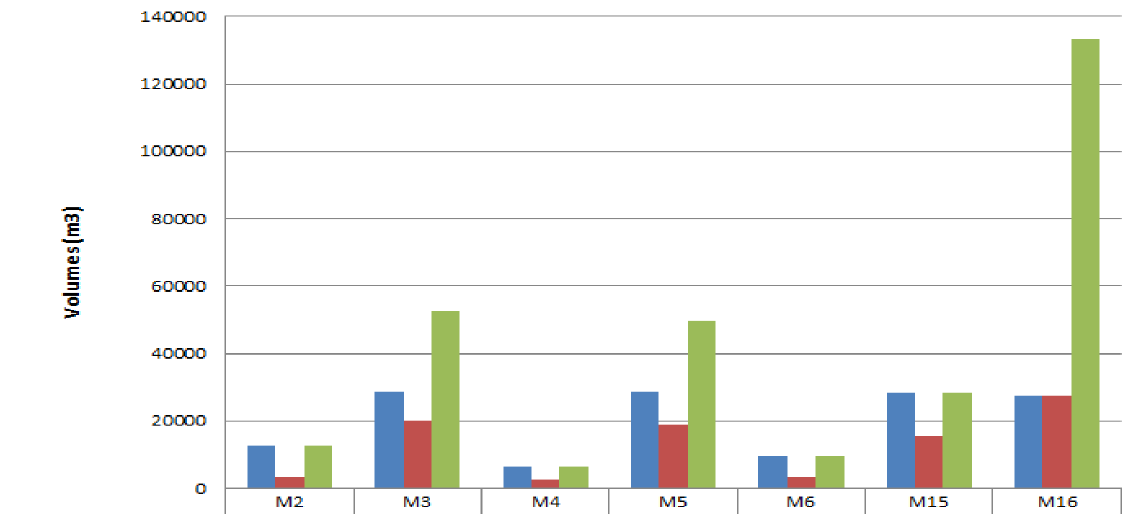


	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16
Ccvalue (ψ_j)	11,4%	6,0%	6,0%	6,0%	6,0%	6,0%	5,9%	1,7%	1,7%	11,4%	5,9%	8,7%	7,3%	5,9%	8,7%	1,7%
Perf.(ω_j)	5,1%	3,5%	3,1%	3,2%	3,8%	2,5%	18,0%	5,9%	3,7%	9,6%	13,5%	7,0%	6,0%	4,2%	5,6%	5,3%

Figure 4.2 – *Contribution to total CS and Individual sustainability performances*

4.1.2 Results of the goal programming model

Here, the volumes of wood to allocate to each mill are determined. For the sake of simplicity, the focus is only on the results obtained for mills processing SPF species. In Figure (4.3), we observe that the obtained wood allocations reflect a balance between the sustainability performances of the mills and their contributions to the total CS. Here, the two goals are considered equally important (they have the same weight). The results show that mills M_2, M_4, M_6 and M_{15} obtain a volume up to their capacity. For mill M_{15}, the volume obtained can be explained by its higher contribution to the CS (8.77%) and its higher sustainability performance score (5.6%) among all mills consuming SPF species. The second best values are obtained by the mill M_5 which gets a volume that exceeds its minimum volume. Mills M_2 and M_4 obtain the maximum volume because these two mills have lower capacities compared to the other mills. The same applies to M_3 and M_6. Mill M_{16} gets its minimum volume because of its lower contribution to CS. We can conclude that the model generates results that are proportional both to the mills' contributions to the CS and their sustainability performances.



	M2	M3	M4	M5	M6	M15	M16
Volumes ($X\_(SPF,J)$)	12780	28707,99999	6390	28707,99999	9480	28230	27349
Vol min(V_qj)	3443	19947	2498	18923	3364	15368	27349
Capacity($K\_(SPF, j)$)	12780	52395	6390	49665	9480	28230	133260

Figure 4.3 – *Allocations obtained for mills processing SPF species*

4.1.3 Sensitivity analysis

Here, the generalized form of the model i.e. the weighted GP with the two goals is considered. The idea is to attach penalty weights to the unwanted deviation variables in the objective function (4.1.1). In fact, we assign, respectively, the weights γ_i and $\bar{\gamma}_i$ to the deviation variables in the objective function, such that: $\gamma_i + \bar{\gamma}_i = 1$. For the sake of simplicity, the same weight is assigned to the negative and positive deviation variables of each goal.

$$\min \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{N}} \sum_{e \in E} \left(\gamma_i \times \left(\delta_{ije}^{(+)} + \delta_{ije}^{(-)} \right) + \bar{\gamma}_i \times \left(\tilde{\delta}_{ije}^{(-)} + \tilde{\delta}_{ije}^{(+)} \right) \right) \tag{4.1.1}$$

The following scenarios are considered based on variations of the weights (γ and $\bar{\gamma}$) and compare their results to the reference scenario shown previously in Figure (4.3).

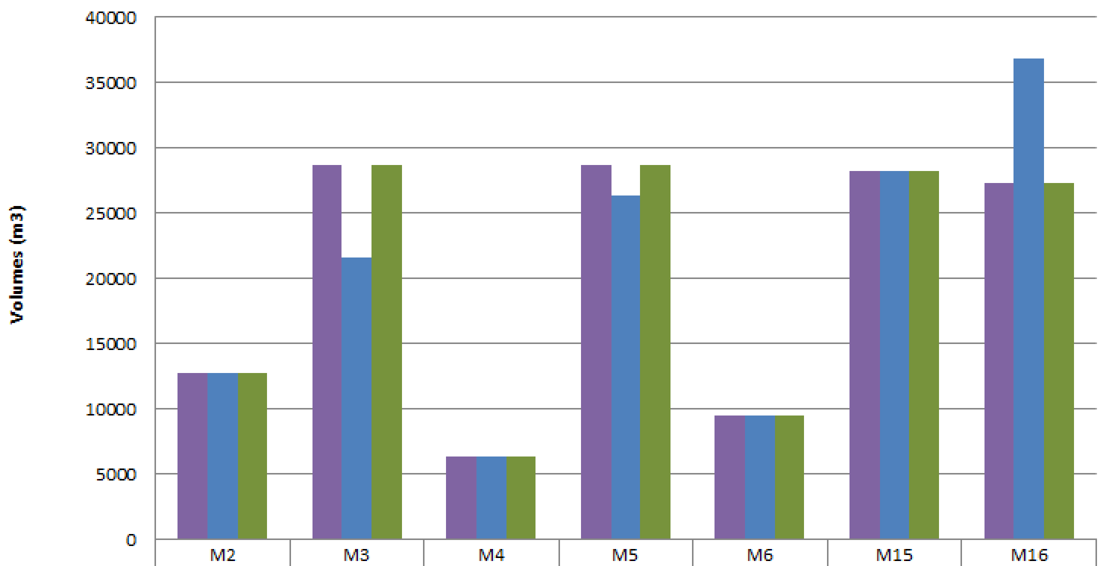
- *Scenario 1*: the allocations are based only on the contributions of the mills to the CS (Goal 1).
- *Scenario 2*: the allocations are based only on individual sustainability performances (Goal 2).
- *Scenario 3*: the allocations are based on both goals to which different weights are assigned:

  (3a) We assign a greater weight to the deviation variables corresponding to goal 1.

(3b) We assign a greater weight to the deviation variables corresponding to goal 2.

Concerning *scenario 3*, a weight γ_i is assigned to the deviation variables corresponding to goal 1 (scenario 3a), which is superior to $\bar{\gamma}_i$. Inversely, in scenario (3b), the weight $\bar{\gamma}_i$ is assigned to the deviation variables corresponding to goal 2 which is superior to γ_i. In scenario (3a), we set $\gamma_i = 0.55$ and perform the calculations of the allocations for each mill. Then we increase γ_i with a path of 0.05 each time and repeat the calculations. Note that $\bar{\gamma}_i = 1 - \gamma_i$.

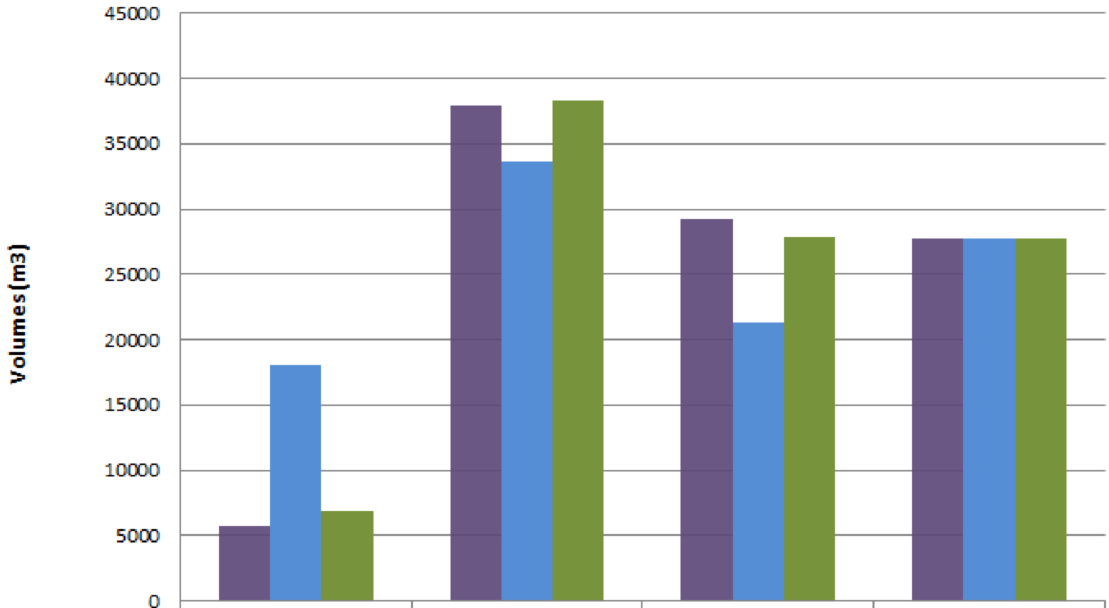
The results of scenarios 1 and 2 are presented in Figure (4.4) and Figure (4.5). First, we observe that the wood volumes allocated to the mills processing SPF species in scenario 1 are the same as in the reference scenario (see Figure (4.4)).



	M2	M3	M4	M5	M6	M15	M16
Scenario 1	12780	28707,99999	6390	28707,99999	9480	28230	27349
Scenario 2	12780	21538,64747	6390	26402,21302	9480	28230	36824,13922
reference scenario	12780	28707,99999	6390	28707,99999	9480	28230	27349

Figure 4.4 – *Allocation for mills processing SPF (scenario 1,2)*

However, we see a difference in the volumes allocated to the mills consuming the other wood species (THUJ, HRDW, POPL). For instance, Figure (4.5) presents the wood volumes allocated to mills processing POPL species, where M_8 obtains a lower volume in scenario 1 compared to the reference case, because M_8 has a lower contribution to the CS (CC value equal to 1.8%). On the other hand, M_8 obtains a higher volume in scenario 2 because it has a higher individual sustainability performance (5.9%). We observe that M_{16} obtains only its minimum volume in scenario 1. In scenario 2 (in which the allocation is made



	M8	M10	M12	M14
Scenerio-1	5768,987802	37981,94859	29245,10001	27772,28361
Scenario-2	17993,39601	33654,54549	21348,09691	27772,28131
reference scenario	6843,109313	38257,11446	27895,81257	27772,28361

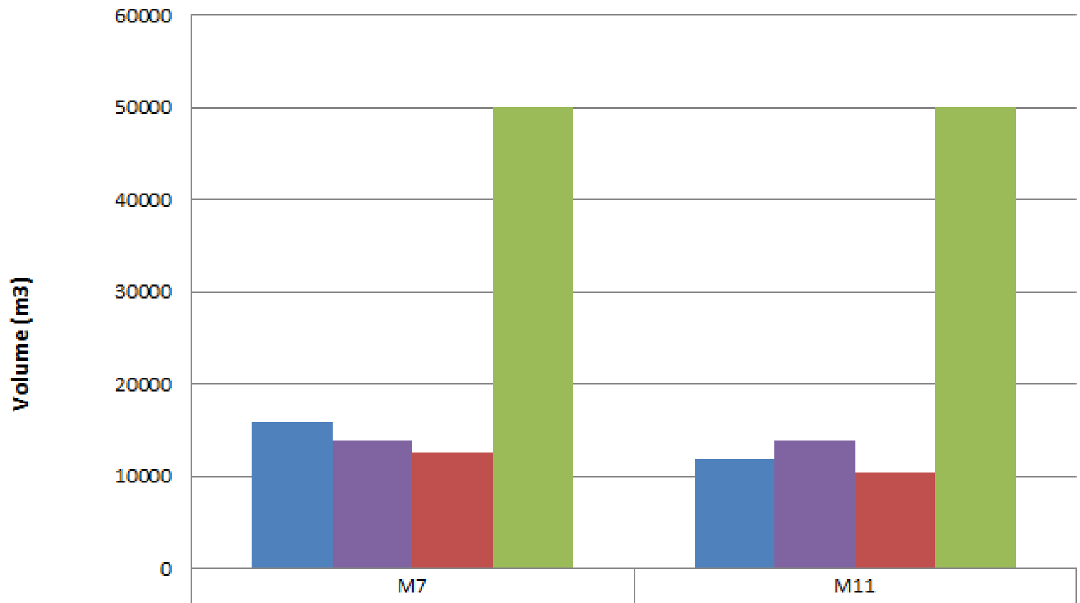
Figure 4.5 – *Allocation for mills processing POPLAR (scenario 1,2)*

proportionally to the individual performances only), we observe that mill M_{16} obtains a higher volume, because its individual performance (5.3 %) is higher than its contribution to the CS (1.45 %), in the one side. Its individual performance is higher than other individual performances, in the other side. Mills M_3 and M_5 have the same contribution to the CS (5.93%), but different individual performances ($\omega_5 > \omega_3$) which explains the higher volume allocated to M_5 compared to M_3 in scenario 2. In scenario 1, mills M_2, M_3, M_4, M_5 and M_6 have the same contribution to the CS; the differences in the volumes allocated is explained by the differences in the processing capacities and the minimum volumes constraints.

Figures (4.6) and (4.7) below present the results of scenarios (3a) and (3b) on THUJ and SPF species, respectively.

Concerning scenario (3a), the results show that the volumes allocated to mills processing SPF do not change compared to the reference scenario and scenario 1, even if the values of γ_i is increased up to 0.95.

This shows that the allocated volumes of SPF species are non-sensitive to the weights assigned to the deviations corresponding to goal 1. This is because, the maximum volume

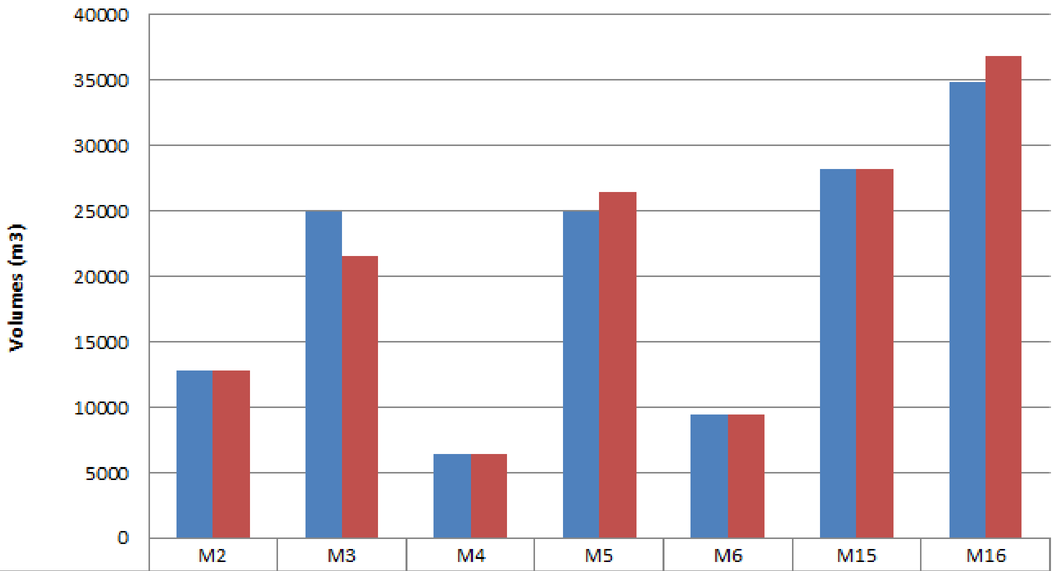


	M7	M11
Scenario 3a (γ<=0.7)	15914,28556	11935,71418
Scenario 3a (γ>0.7)	13925	13925
Volume-min (V_qj)	12650	10450
Capacity($K\_(THYA, j)$)	50000	50000

Figure 4.6 – *Allocations in scenario (3a) for mills processing THUJ*

to allocate to the mills processing SFP species is reached, given their CC values. This is not the case with mills processing THUJ wood species (see Figure (4.6)). We note that individual sustainability performances of M_7 and M_{11} are respectively (18%) and (13.5%) and they have the same contribution to CS (5.9%). Therefore, the volume allocated to M_7 is greater than that of M_{11} for γ_i ranging from 0.55 to 0.7 which corresponds to an allocation proportional to the individual performance (because $\omega_7 > \omega_{11}$). However, for γ_i greater than 0.70, the two mills obtain the same volume of THUJ species which corresponds to an allocation proportional to the CC values of the mills ($\Psi_7 = \Psi_{11}$).

The results of scenario (3b) are presented in Figure (4.7) for mills processing SPF species. We observe that mills that have higher individual performance than their contribution to CS obtain higher wood volumes (SPF species) than in scenario (3a) (see Figure (4.7)). For instance, mill M_{16} obtains a higher volume compared to what it gets in the reference scenario (see Figure (4.3)), in scenario 1 (see Figure (4.4)) and scenario (3a) (see Figure (4.7)). We observe that the more the weight of the deviations corresponding to goal 2 increases, the more the volume allocated to mill M_{16} increases. Its maximum volume (36824 m^3) is reached for $\bar{\gamma_{16}} \geq 0.60$ (see Figure (4.7)). In the case of mills M_3 and M_5,



	M2	M3	M4	M5	M6	M15	M16
Scenario-3b(γ=0.55)	12780	24969,535	6390	24969,53489	9480	28230	34825,93023
Scenario-3b(γ>0.60)	12780	21538,64754	6390	26402,21311	9480	28230	36824,13934

Figure 4.7 – *Allocations in scenarios (3b) for mills processing SPF species*

the relatively low scores obtained regarding their individual performances (3.1 % and 3.8 % respectively) lead to lower allocated volumes. We observe a slight advantage for M_5.

We observe that in all scenarios, mills M_2, M_4, M_6 and M_{15} obtain the maximum possible volumes corresponding to their respective capacities. Mill M_{15} has the highest individual performance and the highest contribution to the CS. Concerning mills M_2, M_4 and M_6, even if they don't have high individual performances scores nor high CC value, the maximum volumes they obtain are explained by their respective processing capacities which are the lowest among all mills, and which can be, therefore, easily satisfied. We observe, for example, that the wood volume allocated to M_{16} is about three times the processing capacity of M_6 in scenario (3b) and more than four times than the processing capacity of M_4.

4.1.4 Results of the stability analysis of the current CC

Since the changes in the coalitions only affect the CC value corresponding to the goal 1, we will base this analysis on its variations (weights of the goal 1) while keeping the mill's individual sustainable performance (weights of the goal 2) fixed in the weighted GP model (4.1.1). Computational experiments are carried on the CC of the harvesting operation for illustration purposes. The results show that the coalitional stability (internal and external)

is only guaranteed with a weight γ varying from 80% to 100%.
Concerning the *internal stability*, we considered the case where a mill leaves a coalition of the CC Θ_h. Next, we calculate the CC value and then the volumes allocated by the weighted GP model. This is repeated for each mill. The results in Table A.1 (in Appendix A.1), show that internal stability is verified for $\gamma = 80\%$. The payoffs of each mill is equal or higher before leaving the coalition than after leaving. The internal stability is also verified for $\gamma > 80\%$.
Concerning the external stability, M_{16} which is a singleton is considered as illustration. We suppose that M_{16} attempts to join the existing coalitions $\beta \in \Theta_h$ of the harvesting operation's CC. The results presented in Table A.2 (see Appendix A.1) show the payoffs of mill M_{16} and those of the members of each coalitions when M_{16} attempts to join them. We observe in each coalition ($\beta_i, i = 1, 2, 3, 4$) that at least one member's payoff is reduced when the mill M_{16} joins them. Consequently, there is no incentive for the coalition members to accept this new partner (M_{16}) in any of their coalitions. This illustrates the external stability of the CC. This approach can be generalized to other operations (transport and road construction and upgrading).

Further investigations could be made around Aumann's Strong Nash Equilibrium [10] and the stability according to [21] for the problem of CC formation. However, this problem is beyond the scope of this study.

4.1.5 Comparison between CC value and Least Core Value (LCV)

Here, we discuss a comparison between CC value and the LC value (2.4.2) which is one of the most popular core stability solution concepts. It is discussed in Section 2.4.

We consider the game: $\upsilon(S) = \alpha_h \times \upsilon_h(S) + \alpha_r \times \upsilon_r(S) + \alpha_t \times \upsilon_t(S)$ such that $\alpha_h + \alpha_r + \alpha_t = 1$ and $\alpha_o \in [0, 1]$ for $o \in O$. We compare the wood volume allocations by the GP model with goal 1 based on the CC value (GP-CC value model) in one hand and with the same goal based on the LC value (GP-LC value model) in the other hand. We keep goal 2 of the GP model, based on individual sustainable performances, unchanged. The results are presented in Figures (4.8), (4.9). The LC value is obtained for $\epsilon = 1.0456$.

These results are obtained by solving the linear programming model (2.4.3) [18], with $\alpha_h = \alpha_r = \alpha_t$. We observe in Figures (4.8) and (4.9), a relative correlation between the GP-CC value model-based allocations and those obtained with GP-LC value model. Nevertheless, in Figure (4.8), we see that the GP-CC value model allocates more SPF volumes for M_3 and M_5 than GP-LC value model, contrary to mill M_{16}. This is in accordance with the

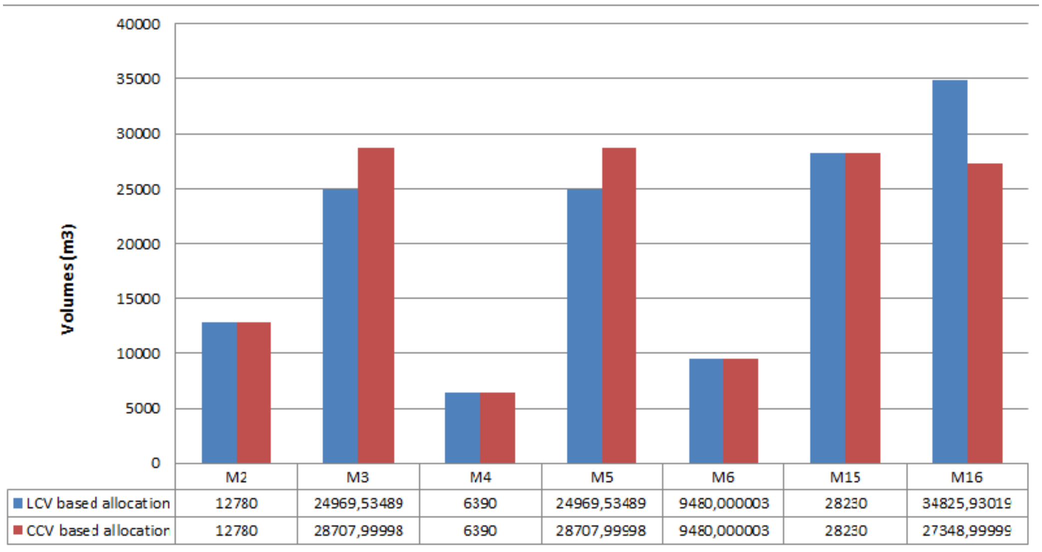


Figure 4.8 – *SPF allocation based on CCV vs LCV*

GP-CC value model, whose goal 1 favors with larger CC values. We note that these two mills collaborate in overlapping coalitions and M_{16} does not participate in any coalition (see M_3, M_5 and M_{16} in Table 3.1). Thus, the GP-LC value model allocates larger volume to M_{16} than GP-CC value model. The GP-LC value model assigns minimum volumes of HRDW species for M_8 and M_9, whereas they are rewarded by GP-CC value model for joining overlapping coalitions (see Figure (4.9) and Table 3.1), by more volumes.

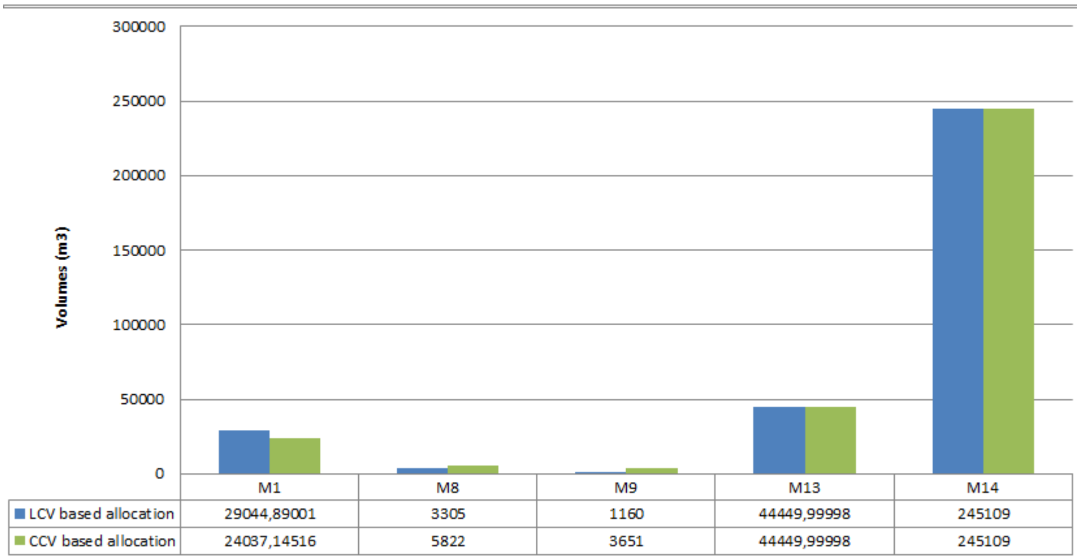


Figure 4.9 – *HRDW allocation based on CCV vs LCV*

The opposite is true for mill M_1.

In the presented case study, we can see that, in addition to the coalitional stability, measuring the marginal contribution of each mill is an argument that's more convincing for the mills to collaborate.

4.2 Results of the allocation based on the aggregation of criteria by the Choquet Integral function

In this section, we present the results of the application of the second allocation method based on the aggregation of the four criteria based on the Choquet Integral function.

4.2.1 Step 0: Criteria selection

As mentioned before, the criteria selected based on which each mill i is evaluated are: Economic (Ec), Environment (Env), Social (S) and Collaboration effort (CE). In other words: $X(i) = \{Ec(i), Env(i), S(i), CE(i)\}$.

4.2.2 Step 1: Mill evaluation

The evaluation of the mills according to the sustainability criteria (Ec, S, Env) are obtained from [15]. Concerning the collaborative efforts (CE) criterion, the evaluations are those obtained in Figure (4.2) and Figure (4.1) of Section 4.1.

4.2.3 Step 2: Fuzzy measuring

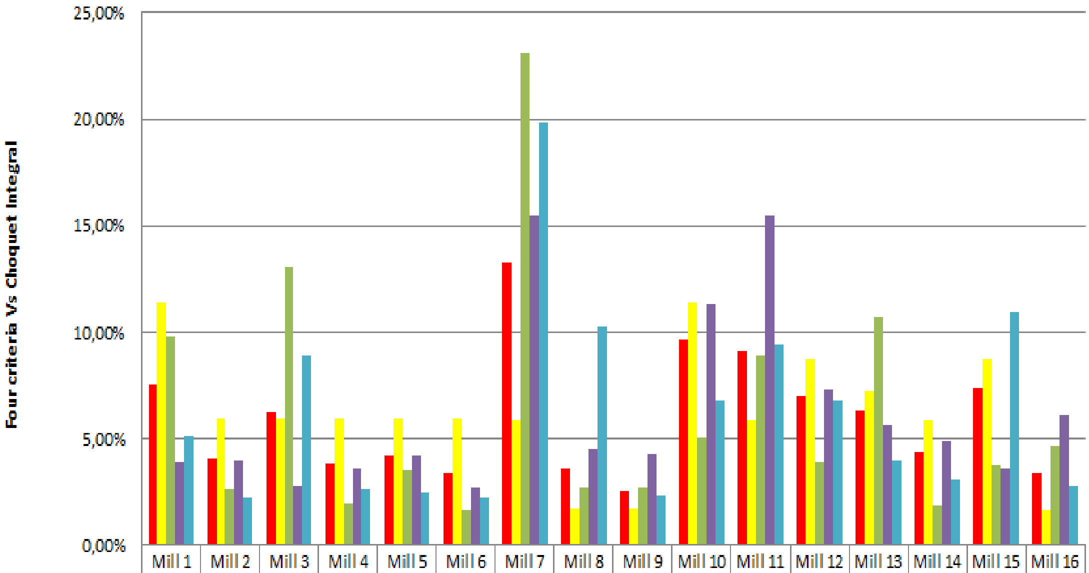
In our case, we have made hypothetical estimations as fuzzy measures to illustrate our approach. These estimations are presented in the Table 4.1:

Table 4.1 – *Fuzzy measure estimations*

$\mu(S) = 0.1$	$\mu(Ec) = 0.2$	$\mu(Env) = 0.1$	$\mu(CE) = 0.3$
$\mu(S, Ec) = 0.4$	$\mu(E, Env) = 0.3$	$\mu(S, CE) = 0.5$	$\mu(Ec, Env) = 0.4$
$\mu(Ec, CE) = 0.7$	$\mu(Env, S) = 0.7$	$\mu(S, Ec, Env) = 0.6$	$\mu(S, Ec, CE) = 0.7$
$\mu(S, Env, CE) = 0.7$	$\mu(Ec, Env, CE) = 0.8$	$\mu(S, Ec, Env, CE) = 1$	/

4.2.4 Step 3: Choquet aggregation

In our case, the aggregated performance of each mill obtained based on the results reported by [15] and Figure (4.2), is presented in Figure (4.10) below. The calculations are performed in the R environment using the Kappalab package [30].

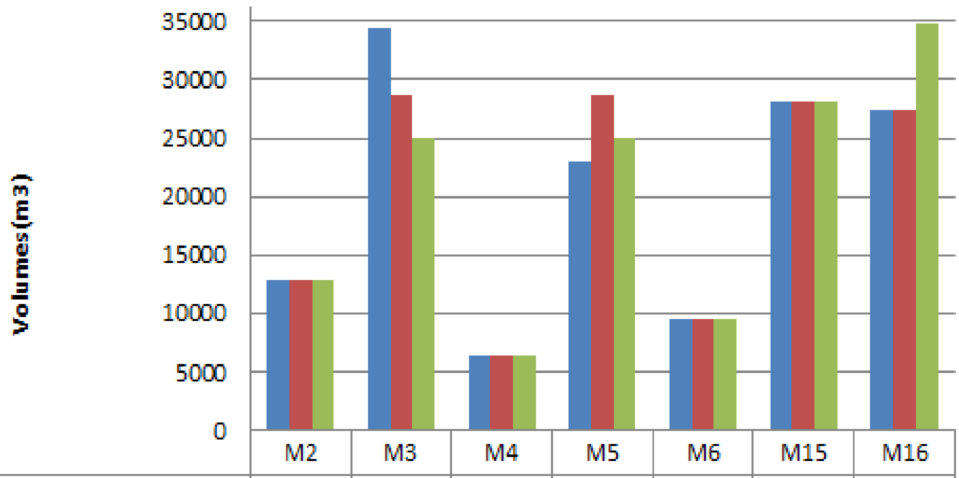


	Mill 1	Mill 2	Mill 3	Mill 4	Mill 5	Mill 6	Mill 7	Mill 8	Mill 9	Mill 10	Mill 11	Mill 12	Mill 13	Mill 14	Mill 15	Mill 16
Choquet Integral	7,57%	4,08%	6,30%	3,89%	4,22%	3,42%	13,3%	3,6%	2,58%	9,64%	9,11%	7,04%	6,31%	4,41%	7,42%	3,37%
Collaboration Synergy	11,39%	5,95%	5,95%	5,95%	5,95%	5,95%	5,87%	1,74%	1,74%	11,39%	5,87%	8,73%	7,25%	5,87%	8,73%	1,67%
Social	9,8%	2,6%	13,0%	2,0%	3,5%	1,6%	23,1%	2,7%	2,7%	5,1%	8,9%	3,9%	10,7%	1,9%	3,8%	4,6%
Economy	3,9%	4,0%	2,8%	3,6%	4,2%	2,7%	15,5%	4,5%	4,3%	11,3%	15,5%	7,4%	5,7%	4,9%	3,6%	6,1%
Environment	5,1%	2,3%	8,9%	2,6%	2,5%	2,3%	19,9%	10,3%	2,4%	6,8%	9,4%	6,8%	4,0%	3,1%	11,0%	2,8%

Figure 4.10 – *The performances of the mills based on Choquet-CCV method*

4.2.5 Step 4: Wood allocation

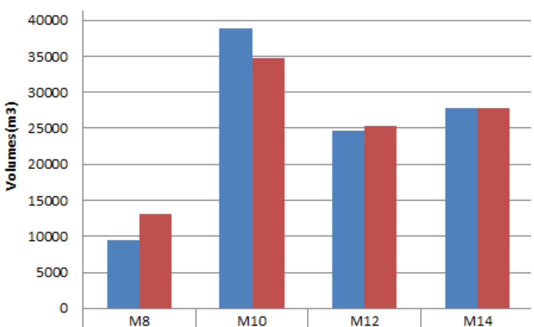
Figure (4.11) presents the results of the Choquet-CCV based allocations for the wood SPF species. We compare these allocations with those obtained based on the CCV and LCV in Figure (4.3) and Figure (4.8) respectively. The results show that Choquet-CCV based allocation grants a higher volume to $mill_3$ because of its relatively higher aggregated performance (6.3%). It has also relatively higher scores according to the social and environmental criteria unlike $mill_5$ (see in Figure (4.10)). Thus, we can observe that Choquet-CCV based allocations rewards the mill's according to the four criteria. The volume obtained by $mill_{16}$ is higher when the allocation is based on the LCV only because of the coalitional stability considerations.(see Section 4.1.5).



	M2	M3	M4	M5	M6	M15	M16
Choquet_CCV based allocation	12780	34407,58	6390	23008,42	9480	28230	27349
CCV based allocation[6]	12780	28708	6390	28708	9480	28230	27349
LCV based allocation[6]	12780,0	24969,5	6390,0	24969,5	9480,0	28230,0	34825,9

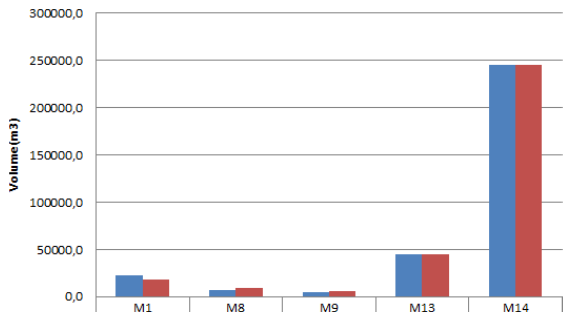
Figure 4.11 – *Volumes allocated to mills processing SPF species obtained based on the Choquet-CCV method, the CCV and the LCV*

A sensitivity analysis involving changes in the weights of the goal programming model is discussed in Section 4.1.3. We could also change the importance of the criteria in the fuzzy measure (Table 4.1) and observe changes in the allocated volumes. Here, we propose a comparison between an allocation based on the Choquet-CCV and the Choquet-LCV, where the *collaborative effort* criterion is calculated with the LCV. The mills processing SPF species obtain the same volumes according to the two allocations methods. However, the results obtained for the wood species POPLAR and HRDW (maple, yellow birch, other hardwoods), presented in Figures (4.12a and 4.12b) are different. The CCV measures



	M8	M10	M12	M14
Choquet-LCV	9509,180499	38867,62126	24619,23754	27772,2817
Choquet-CCV	13020,16645	34662,73037	25313,14276	27772,2817

(a) *Allocation for mills processing POPLAR species*



	M1	M8	M9	M13	M14
Choquet-LCV	22541,4	6671,7	4296,7	44450,0	245109,0
Choquet-CCV	18418,7	8811,0	6280,2	44450,0	245109,0

(b) *Allocation for mills processing HRDW*

Figure 4.12 – *Results of the comparison between Choqeut-CCV based allocation vs Choquet-LCV*

mills' marginal contributions to collective gain. Whereas, the LCV tries to minimize the maximum dissatisfaction of the mills over all possible allocations and it is one of the most popular core stability solution concept. By stability, we mean the absence of any incentive for mills to leave an existing coalition and for the coalition to welcome a newcomer. We observe that the Choqet-LCV model allocates larger volume to $mill_{10}$ than the Choquet-CCV does to maintain the stability of the configuration of the coalitions. Furthermore, there is a margin of progress to minimize its maximum dissatisfaction among the other allocations, inversely to $mill_8$ concerning the two wood species POPLAR and HRDW.

4.3 Conclusion of the chapter

This chapter describes the results of the computational experiments based on real data (except for the fuzzy measure of the CI). In the first method, data were obtained through a field survey. The results of the calculations we carried out showed consistency between the results obtained and the objectives of fair treatment of the mills we set ourselves at the outset.

We even demonstrated the stability (and the coalitional stability conditions) of the solutions provided by our method. In addition, the sensitivity analysis proved the adaptability and the flexibility of our methods to the needs and requirements of the decision makers. We compared the results obtained based on the coalition configuration value with those obtained by another cooperative game solution concept which is the least core value. It's true that other avenues of comparison could be chosen. For instance, another solution concept that takes into account the overlapping aspect of the coalitions could be used. This will be done in future research projects.

General Conclusion

This thesis contributes to the scientific literature by proposing a new approach for the problem of natural resources allocation which requires a close attention due to the increasing competition among companies for limited resources and public requirement for a more sustainable management. The effect of collaboration on forest resources allocation decisions and how collaboration could be explicitly considered in the allocation process are studied .

To do so, an approach based on recent developments in cooperative game theory is designed, based on *the coalition configuration value*, that takes into account the overlapping aspect of the coalitions formed by the players. We have shown that theses concepts capture well real-world resources allocation problem. The proposed approach promotes equity and sustainable resource management.

From managerial insights, the proposed approach can be used as a guiding framework for decision-makers involved in the problem of public-owned natural resources allocation. Currently, the allocation problem involves two main parties: the government and the mills. Therefore, the government as policymaker, should have a global vision on the wood sector exploitation (extraction, transformation, etc.). However, several partners are directly or indirectly involved through other important activities linked to the rich wildlife, and the various outdoor activities in the forest. Moreover, the First Nations who own rights in the forest and private forest owners should be associated in the design of a collaborative mechanism around global sustainability objectives. Indeed, cost savings achieved through collaboration (or potentially achievable if collaboration among mills takes place) could be included in the surveys of the operating costs made by the government, as well as its impact on the above-mentioned involved parties. Note that mechanisms for collaboration between these parties already exist, but hold potential for better refinement. Thus, this approach, through the process of the formulation of the goals, offers a framework making the negotiation processes more efficient for each side, while promoting equity and sustainable development favors and improving the competitiveness of companies at the regional and international markets.

Many other possible scenarios could be imagined in this study, through changes to the parameters of the model: the weights of the goals and the deviation variables, the constraints, etc. according to the needs of the decision-maker and preferences. Future research may investigate more the collaboration aspects such as the collection of more accurate data for a more adequate estimation of the characteristic function of the cooperative game. A deeper analysis of the stability of the coalitions, based on game theory, could lead to a more advantageous coalition configuration of the companies. In addition, other aggregation techniques could be used to better capture the importance of the three operations of the forest supply chain such as those based on multi-criteria or statistics analysis. Another perspective is to carry out a study to develop a bargaining process for forming coalition configurations, combining the interests of firms and the preferences of public authorities, which would certainly produce other coalition configurations.

Appendices A

A.1 Appendix: Coalitional stability analysis

The results of the internal and external coalitional stability analysis are presented in Tables A.1 and A.2.

Table A.1 – *Internal stability of the CC of harvesting operation*

Mills	**Wood species**	**Π_i: Before moving**	**Π_i: After moving**
M_1	HRDW	24727	24552,97
M_2	SPF	12780	8530,27
M_3	SPF	28708	19947
M_4	SPF	6390	6390
M_5	SPF	28708	18923
M_6	SPF	9480	8129,25
M_7	THYA	13925	12650
M_8	POPL+HRDW	11403,2	3305
M_9	HRDW	4391	1160
M_{10}	POPL	39483	38993,61
M_{11}	THYA	13925	10450
M_{12}	POPL	26501	15150,72
M_{13}	HRDW	44450	44450
M_{14}	POPL+HRDW	272881,3	272881,3
M_{15}	SPF	28230	17814,37
M_{16}	SPF	27249	27249

Table A.2 – *External coalitional stability*

β_1	**Wood species**	Π_i: **Before joining** M_{16}	Π_i: **After joining** M_{16}
M_2	SPF	12780	12780
M_3	SPF	28708	28708
M_4	SPF	6390	6390
M_5	SPF	28708	28708
M_6	SPF	9480	9480
M_7	THYA	13925	13925
M_8	POPL+HRDW	11403,2	10547,25
M_9	HRDW	4391,5	4123,05
M_{11}	THYA	13925	13925
M_{13}	HRDW	44450	44450
M_{14}	POPL+HRDW	272881,3	272881,3
M_{16}	SPF	27349	27349

(a) *Payoffs when mill M_{16} joins coalition β_1*

β_2	**Wood species**	Π_i: **Before joining** M_{16}	Π_i: **After joining** M_{16}
M_7	THYA	13925	13925
M_{11}	THYA	13925	13925
M_{12}	POPL	26500,9	25323,8
M_{13}	HRDW	44450	44450
M_{14}	POPL+HRDW	272881,3	272881,3
M_{15}	SPF	28230	28230
M_{16}	SPF	27349	27349

(b) *Payoffs when mill M_{16} joins coalition β_2*

β_3	**Wood species**	Π_i: **Before joining** M_{16}	Π_i: **After joining** M_{16}
M_2	SPF	12780	12780
M_3	SPF	28708	28708
M_4	SPF	6390	6390
M_5	SPF	28708	28708
M_6	SPF	9480	9480
M_{12}	POPL	26500,9	25292,8
M_{15}	SPF	28230	28230
M_{16}	SPF	27349	27349

(c) *Payoffs when mill M_{16} join coalition β_3*

β_4	**Wood species**	Π_i: **Before joining** M_{16}	Π_i: **After joining** M_{16}
M_1	HRDW	24726,9	21893,1
M_{10}	POPL	39482,9	33654,5
M_{16}	SPF	27349	35787,757

(d) *Payoffs when mill M_{16} join coalition β_4*

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Agzul s tmaziɣt

Asmugen n umikanizm amellil i uḥeṛṛi n tesmekta timilist n teɣbula tigamanin n baylek, yellan ddaw ufus n Uwanek, d ayen yellan d anaẓar. Aṭas n yisfernen yemgaraden umi ilaq ad yettunefk wazal, gar-asen : asemɣer n wazal n teɣbula akked tnigit n tgadda d teɣdemt gar yimenyaf (wid umi ara ttunefkent teɣbula-ya). Iban-d wugur-a arafrar (uddis) deg temnaḍt n Kibak (deg Kanada) anda tiɣbula n teẓgi, i yellan d ayla n baylek, ilaq ad tent-yefk udabu i temsuknin (luzinat) yettemsazzalen anwa ara yifen wayeḍ. Deg tezrawt-a, ad d-nsumer tamyadest (anekmar) ara yesdaklen gar tmudemt n wurar anmirgan d tmudemt n usekkey tagtiswit akken ad d-ibin wamek ara yili usbadu n tesmektiwin n teɣbula n teẓgi ara yettunefken i temsuknin yemgaraden. Tamyadest-a tekkat ad d-tger ibuɣar n umyalel (amɛiwen) gar temsuknin akked wayen texdem yal yiwet seg-sent deg wayen ara asent-yettunefken war ma yella-d usenɣes deg wazal n tgadda ara yilin gar-asent. S tseddi, ad nefk azal i umyalel i yellan gar temsuknin deg usiweḍ n tanga tamezwarut (tagmert, alday d useggem n yiberdan akkeḍ ttawilat n usiweḍ) i d-igellun s usenɣes n ssuma, rnu ɣer-s tamlilt tanimant n yal tamsukent (ayen yerzan tadamsa, ayen yerzan tawennaḍt akked wayen yerzan timetti). Udmawen n tdukli d umyalel deg tegnit-a ttemyekcamen, ɣef waya ara nessemres immekti : *azal n twila n tdukli d umyalel*. S tseddi, ad d-nsumer yiwet n tarrayt n uskazal yersen ɣef tnefka i d-yettwagemren. Ad neskazel yerna ad neskasi ibuɣar n temyadest-nneɣ s ttawil n termitin tisenselkimin i yettwaxedmen ɣef tezrawt n tegnit tanilawt. Deg temyadest-nneɣ, ad nefk azal i temyigawin gar temsuknin, daɣen i temyigawin gar yisfernen, d ayen ara d-yilin s lmendad n uɣred n *Choquet*. S wakka, tamyadest-nneɣ yezmer ad tt-isemres udabu deg usefrek n teɣbula tigamanin n baylek.

ملخص

مثل تصميم آلية فعالة لتخصيص كمية محدودة من الموارد الطبيعية المملوكة للقطاع العام للشركات المتنافسة تحدياً. إذ يجب النظر في العديد من المعايير المختلفة مثل تعظيم قيمة الموارد وضمان العدالة بين المستفيدين، على سبيل المثال لا الحصر. وقد لوحظت هذه المشكلة المعقدة في مقاطعة كيبيك (كندا). في هذه الدراسة، نقترح نهجًا متكاملًا يجمع بين نموذج لعبة تعاونية ونموذج تحسين متعدد الأهداف لتحديد كميات موارد الغابات التي يجب تخصيصها للعديد من المطاحن. يحاول هذا النهج الاستفادة من مزايا التعاون والأداء الفردي للمطاحن في عملية التخصيص، مع تعزيز المساواة فيما بينها. وبشكل أكثر دقة، نأخذ في الاعتبار التعاون بين المطاحن في سلسلة التوريد الأولية (أي الحصاد، وبناء الطرق، وعمليات النقل) لتقليل التكاليف التشغيلية بالإضافة إلى أداء الاستدامة الفردية (الجوانب الاقتصادية والبيئية والاجتماعية). تتداخل الائتلافات في دراسة الحالة الخاصة بنا وبالتالي نستخدم مفهوم قيمة تكوين الائتلافات. وعلى وجه الخصوص، نقترح منهجية لتقديرها بناءً على البيانات التي تم جمعها. ونقوم بتقييم ومناقشة مزايا نهجنا من خلال تجارب حسابية تم إجراؤها على دراسة حالة حقيقية. في نهجنا نأخذ بعين الاعتبار التفاعلات بين الطواحين وكذلك التفاعلات بين المعايير بفضل دالة شوكيه المتكاملة. وبالتالي، يمكن استخدام نهجنا كدليل إرشادي

. الكلمات المفتاحية:تخصيص موارد الغابات، قيمة تكوين الائتلاف، تكاملية تشوكيه، برمجة الأهداف نظرية اللعبة التعاونية

Abstract

Designing an effective mechanism to allocate a limited amount of public owned natural resources to competing companies is challenging. Many different criteria such as maximizing the value of the resources and ensuring equity among the beneficiaries, must be considered. This complex problem is observed in the province of Quebec (Canada). In this study, we propose an integrated approach combining a cooperative game model and a multi-objective optimization model to determine the quantities of forest resources to allocate to several mills. This approach attempts to capture collaboration benefits and mills individual performances in the allocation process, while promoting equity among them. More precisely, we consider collaboration between mills in the upstream supply chain (i.e., harvesting, road construction/upgrading, and transportation operations) to reduce operational costs as well as their individual sustainability performances (economic, environmental and social aspects). The coalitions of our case study overlap and thus, we use the concept of coalition configuration value. In particular, we propose a methodology for its estimation based on the collected data. We evaluate and discuss the advantages of our approach through computational experiments performed on a real case study. In our approach we consider interactions among mills, but also interactions among criteria thank to the Choquet Integral Function. Thus, our approach could be used as a guiding framework for decision-makers involved in the important problem of public-owned natural resource allocation.

keywords: Forest resources allocation, Coalition configuration value, Choquet Integral, Goal programming, Cooperative game theory.

Résumé

Concevoir un mécanisme efficace pour allouer une quantité limitée de ressources naturelles publiques, à des entreprises concurrentes est un défi. De nombreux critères, tels que la maximisation de sa valeur et la garantie de l'équité entre les bénéficiaires, doivent être pris en compte. Ce problème complexe est observé dans la province de Québec (Canada) où les ressources forestières publiques doivent être allouées par le gouvernement à de multiples usines concurrentes. Dans cette étude, nous proposons une approche intégrée combinant un modèle de jeu coopératif et un modèle d'optimisation multi-objectifs pour déterminer les quantités de ressources à allouer à ces usines. Cette approche tente d'intégrer les avantages de la collaboration et les performances individuelles des usines dans le processus d'allocation, tout en promouvant l'équité entre elles. Plus précisément, nous considérons la collaboration entre les usines dans la chaîne d'approvisionnement en amont (c'est-à-dire la récolte, la construction/amélioration des routes et le transport) afin de réduire les coûts opérationnels. Nous tenons aussi en compte leurs performances individuelles en matière de durabilité (aspects économiques, environnementaux et sociaux). Les coalitions de notre cas d'étude se chevauchent et nous utilisons donc le concept de valeur de configuration de la coalition. En particulier, nous proposons une méthodologie pour son estimation basée sur les données collectées. Nous évaluons et discutons les avantages de notre approche par le biais d'expériences informatiques réalisées sur une étude de cas réelle. Nous considérons les interactions entre les usines, mais aussi les interactions entre les critères grâce à l'intégrale de Choquet. Ainsi, notre approche pourrait être utilisée comme cadre d'orientation pour les décideurs impliqués dans problème de l'allocation des ressources naturelles.

Mots-clés: Allocation des ressources forestières, Coalition configuration value, Intégral de Choquet, Goal programming, Théorie des jeux cooperatifs