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ORIGINAL ARTICLE

Horizontal collaboration in the wine supply chain planning: A Chilean case study

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ABSTRACT
The wine industry faces a highly competitive environment, making cost-effective management of the wine supply chain essential. Literature has shown that this objective can be achieved with the implementation of horizontal collaboration strategies in logistics. In this strategy, firms located at the same level of the supply chain cooperate to reduce costs, improve quality of service and mitigate environmental externalities. This paper analyses the implementation impacts of a horizontal collaboration policy in the wine supply chain. To do so, we propose a cooperative game with transferable costs, in which the characteristic function is obtained by solving a novel linear programming formulation that models the joint planning of the wine supply chain. To evaluate the benefits of collaboration, we conduct a case study involving three of Chile's largest wineries. The results show that the use of collaborative frameworks leads to significant reductions in the logistics costs of the wine supply chain. Furthermore, we find that the grand coalition reduces the costs by 10.17% compared to the non-collaborative case. This reduction comes mainly from a decrease in the bulk wine inventory cost. We also analyse the impact of coordination costs on the savings and conduct a sensitivity analysis.

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KEYWORDS
Wine supply chain; horizontal collaboration; linear programming; cost allocation; case study

1. Introduction

The wine industry's contribution to the economy is relevant in wine-producing countries. In Chile, for example, the sector represents 0.5% of the GDP, providing an important employment source. The wine industry is quite competitive, particularly in international markets, where many wineries compete for profits. On this, wineries are usually in a position of weakness when negotiating with key players such as large retail chains or state-owned monopolies (e.g. Systembolaget in Sweden), making obtaining revenues even harder.

To maximise profits, wineries must keep their costs as low as possible. The wine supply chain provides several opportunities for reducing logistics costs using a horizontal collaboration approach. This practice, which refers to the collaboration of firms that perform similar activities and operate at the same level of the supply chain, involves the sharing of resources and information that could reduce the inefficiencies that arise in this chain. These include, among others, empty wine truck miles, low cellar storage, poor bottling utilisation, and a costly last mile.

There are some initiatives that have fostered collaboration within the Chilean wine industry. A successful example is 'Wines of Chile' organisation, whose primary objective is to position the "Chile" brand around the world through advertising. Moreover, due to the above-mentioned hypercompetitive environment, collaboration in the wine industry might be pushed forward to include some logistics activities in order to improve efficiency.

This research analyses the impact of using a horizontal collaborative approach to improve logistics decisions for multiple wineries. Particularly, we assess how several wineries benefits of the joint planning of four logistic activities: (i) the transportation of bulk wine from the fermentation cellars to the bottling plants, (ii) the bottling process, (iii) the storage of the final product in bottling plants, and (iv) the transportation of the final product to ports.

To the best of our knowledge, there are only four previous papers that have used operations research tools to model the wine supply chain holistically. The first three ones correspond to Azaron et al. (2008), Varsei and Polyakovskiy (2017) and Fragoso and Figueira (2021), which focus on developing multi-objective optimisation models to support the design of the wine supply chain. The fourth one corresponds to Taghikhah et al. (2021), which uses simulation tools to study organic farming adoption in the wine supply chain. However, neither paper

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focuses on aspects of horizontal collaborative logistics.

Indeed, the only two contributions in terms of horizontal collaboration in this industry consider one stage of the wine supply chain only. These stages are the bottling process (Basso et al., 2020) and the grape harvesting process (Varas et al., 2022). Therefore, there is a research gap in using optimisation and cooperative game models to evaluate the benefits of collaboration when jointly planning the logistics activities across the entire wine supply chain.

The contributions of this article are three-fold. First, we develop a novel mixed-integer linear programming model allowing the harvesting, vinification, bottling, and transportation stages to be simultaneously planned for several wineries. Second, we model collaboration between wineries as a cooperative game with transferable costs. In this case, the characteristic function is derived from the optimal solutions of the proposed optimisation model. Finally, we analyse the benefits of collaboration by conducting a case study that includes three of the four largest wineries in Chile.

The remainder of this document is organised as follows. Section 2 reviews both the literature on operations research applied to the wine industry and relevant applications of collaborative logistics. In Section 3.2, the supply chain planning problem in the wine industry is described, and the collaborative model is formulated. In Section 4, we conduct a case study to assess the impact of the proposed approach. Finally, in Section 6, we conclude with some final observations, and guidelines for future research are established.

2. Literature review

2.1. Operations research in the wine supply chain

There are four main stages in the wine supply chain: harvest, wine manufacturing, packaging, and distribution (Basso et al., 2020). All of these stages have been studied using Operations Research tools (Moccia, 2013), which has allowed the implementation of Decision Support Systems to improve the chain efficiency (Michalewicz et al., 2010).

In the grape harvest stage, Ferrer et al. (2008) formulates an optimisation model to support harvest planning, incorporating the effects of grape quality loss. The model considers grape reception capacity constraints and field routing decisions for both machinery and workers. For the same problem, Bohle et al. (2010) incorporates uncertainty in worker productivity using a robust optimisation model, while Arnaout and Maatouk (2010) develops a heuristic solution approach to cope with a large number of fields. Varas et al. (2020) proposes a multi-objective mixed-integer optimisation model to tackle the problem of harvest scheduling, considering the opposite objectives of cost reduction and maximisation of grape quality. Avanzini et al. (2021) proposes a Markov chain approach to consider weather uncertainty during the grape harvest process. The authors compare an expected value with a multi-stage stochastic optimisation approach using standard metrics, finding that the latter produces better results. Finally, Varas et al. (2022) proposes a collaborative approach to the grape harvesting problem. The authors devise a novel cost-sharing method that uses the Gini index as a fairness criterion.

In the wine manufacturing stage, Cakici et al. (2006) proposes an integer optimisation model that minimises wine damage and optimises the resources usage of tanks and pipe networks. The optimisation model has limited utility for large-scale instances, so the authors propose a heuristic approach. Van der Merwe et al. (2011) presents a nested tabu search approach that simultaneously addresses the problems of grape harvesting and tank assignation. The authors conduct a case study in South Africa to assess the proposed methodology's feasibility in a real-world setting. Palmowski and Sidorowicz (2020) uses a stochastic dynamic programming approach to determine the optimal strategy for assigning grapes to press tanks. The authors show that applying the algorithm to a Portuguese winery increase daily income by 135,000€ compared to the experience-based method. Finally, Carneiro et al. (2021) formulates an optimisation problem to address the reception of the grape, implementing a genetic algorithm to obtain solutions efficiently. Compared to the FIFO policy output, the proposed approach significantly decreases truck and grape waiting times.

In the packaging stage, Cholette (2009) and Varas et al. (2018) study the impact of postponement strategies for bottling and labelling processes to mitigate demand uncertainty using a two-stage and a multi-stage stochastic programming approach, respectively. Both papers concur that some level of postponement is always recommendable. Basso and Varas (2017) study the scheduling problem that arises when jobs are assigned to parallel bottling lines. The authors propose a mixed-integer linear formulation and a heuristic solution approach, finding that the proposed methodology considerably reduces delays in the jobs. Varas et al. (2018) proposes a $(s-1,s)$ model to manage premium wines inventory. The authors propose a heuristic solution approach, obtaining good results, especially when using a priority policy for the labelling process.

Finally, in the distribution stage, Cholette (2007) proposes a mixed-integer programming approach to match wineries and distributors. The parameters of the model are extracted from the responses to a questionnaire. The model recommends 31 of the 675 possible pairings between wineries and distributors. Hekimoğlu et al. (2017) proposes a two-stage stochastic programming approach with recourse to support wine distributors' decision-making under climate and market uncertainty. Using data from a large-sized wine distributor, the authors show that the proposed method increases the average profit by more than 21%.

The papers reviewed so far focused on just a few stages of the wine supply chain. Instead, the optimisation model developed in this spans the four stages of the wine supply chain in a similar way to Varsei and Polyakovskiy (2017) and Fragoso and Figueira (2021). These two contributions propose multi-objective models to incorporate sustainability variables in wine supply chain management. On the other hand, our paper presents an optimisation model to study the collaboration of several wineries, allowing resource sharing and joint planning of some parts of the wine production process. Similarly to Basso et al. (2020), we use cooperative game theory to analyse the potential benefits of the collaboration. Differently from their work that focuses on cooperative wine bottling, we study cooperation for the whole wine supply chain. Contrary to most of the reviewed papers, we take a tactical point of view, considering production, inventory, and transportation variables on a weekly basis.

2.2. Collaborative logistics

In collaborative logistics, two or more companies work together to improve their operational performance. These improvements include cost reduction (Vanovermeire et al., 2014), emissions reduction (Pérez-Bernabeu et al., 2015), or improving service quality (Wadhwa et al., 2006). There are two types of collaboration in logistics, namely, vertical or horizontal (Mrabti et al., 2021). The former refers to the collaboration that occurs between members of the same supply chain (Simatupang & Sridharan, 2002; Borodin et al., 2016; Zhang et al., 2018). An example of vertical collaboration is in the exchange of information within a supply chain to reduce the consequences of the bullwhip effect (Audy et al., 2012; Wang & Disney, 2016). On the other hand, horizontal collaboration occurs when members who are at the same level of the supply chain coordinate part of their logistics activities. This type of collaboration is less studied in the literature as it entails some additional practical difficulties, such as the risk of this collaboration being viewed as collusion (Basso et al., 2019, 2021).

Typical modelling frameworks in horizontal collaboration often consist of comparing scenarios with different levels of cooperation while determining its potential benefits and practical implementation difficulties. These analyses are made using qualitative or methodologies quantitative (Sheffi et al., 2019). The qualitative methodologies include case studies (Naesens et al., 2007; Badraoui et al., 2020), interviews (Simmer et al., 2017; Akbar et al., 2020) and focus groups (Rodrigues et al., 2015; Lotfi et al., 2021). Among the quantitative methodologies, which is the view we adopt in this paper, cooperative game theory and operations research are usually employed to analyse economic and operational aspects of the collaboration, although distributed artificial intelligence is also used for modelling cooperation (Kumar et al., 2013). Roughly, two types of cooperative games are used in the horizontal collaboration literature. The more general one is called the Partition Function Game (Thrall & Lucas, 1963), in which it is assumed that the cost of a coalition depends not only on its members but also on the way the other players are grouped. These kinds of games are more common in economics (Pintassilgo & Lindroos, 2008; Csercsik & Kóczy, 2017; Csercsik et al., 2019) with the only exception of Basso et al. (2021) that also consider logistics aspects. The second one, which is the approach we follow in this paper, is called Characteristic Function Game (CFG). These games assume that the value of a coalition depends only on its members' behaviour. Application of CFGs are abundant in collaborative logistics, including the furniture (Audy et al., 2011), healthcare (Mohebbi et al., 2020), energy (Flisberg et al., 2015) and forestry (Frisk et al., 2010) industries.

Several logistical problems have been addressed using a horizontal collaboration approach, being the transportation activity the most studied (Guajardo & Rönnqvist, 2016). This is explained since the transportation stage is relatively standard and, in general, not part of the producer's primary activities. Over the past years, the collaborative vehicle routing problem (CVRP) has gained the attention of researchers. For a comprehensive review, we refer the reader to Gansterer and Hartl (2018). On this, the seminal paper Göthe-Lundgren et al. (1996) proposes CVRP in which customers share dispatch costs considering a homogeneous fleet. This assumption is relaxed in Engevall et al. (2004), and the resulting model is applied to support an oil and gas product dispatch problem.

Except for a handful of papers, there is little research on horizontal collaboration in a supply chain network configuration (SCNC) framework

(Bahinipati et al., 2009). This occurs mainly because, as decisions in SCNC are usually located at a strategic level, then a long-term commitment is required, thus implying the need for high trust and coordination levels (Pomponi et al., 2015). Moreover, such agreements could attract the attention of anti-trust authorities (Basso et al., 2021). Nevertheless, there are some exceptions in horizontal collaboration in SCNC. Verdonck et al. (2016) proposes a cooperative carrier facility location problem. The authors find that sharing distribution centres may lead to significant cost savings up to 21.6%. Ouhader and El Kyal (2017) analyse the impact of collaborative depot location and routing in urban road freight transportation. The authors use a multi-objective optimisation formulation and the ε-constraint solution approach to assess the benefits of collaboration, finding that emission costs can be reduced up to 52.9%. Gao et al. (2019) studies the benefits of collaborative SCNC among three potential bio conversion facilities in British Columbia, Canada. The authors find that the grand coalition is the best outcome, achieving a 5% increase in the total net present value.

Despite other sectors, little emphasis has been given to the study of vertical or horizontal collaboration in the wine supply chain industry (Basso et al., 2020). This lack of papers in the wine industry contrasts with other sectors, such as in forestry (Frisk et al., 2010; Guajardo et al., 2018; Basso et al., 2021) or healthcare industries (Bentahar, 2018; Skinner et al., 2021; van der Schors et al., 2021), in which horizontal collaboration has been much more studied. A possible explanation for this is that, unlike other supply chains, winemaking has very specific processes that are difficult to make outside the winery. Consequently, a distinctive feature of our modelling approach is that it is flexible enough to allow cooperation in only some processes of the wine supply chain. Also, as opposed to previous efforts, we include transaction (or moral) costs when computing the characteristic function. These costs are relevant in our case since wine is not a commodity (Neacsu & Madar, 2016), as is the case of wood (Björheden & Helstad, 2005), for example. Thus, some wineries might be reluctant to cooperate to avoid losing control over the processes (Gąsowska, 2017), which might increase the risk of their wine being contaminated or damaged. The proposed transaction costs help to take into account these issues, which have been pointed out as a relevant research path in previous papers (Ferrell et al., 2020).

3. Collaboration between wine supply chains

The wine supply chain involves all logistic activities needed to fulfil wine orders at the lowest cost possible. This chain comprises four stages: harvest, wine manufacturing, packaging, and distribution. In the harvest stage, grapes of different types are harvested in the fields depending on the winery's requirements. Then, in the wine manufacturing stage, the harvested grapes are transported to the cellars, where fermentation is carried out in tanks as per the enologist's indications. Once the fermentation time has elapsed, the wine can be transported to the bottling plants, where the packaging activities are developed. Finally, in the distribution stage, bottled wine is either sent to the port or stored in inventory on-site.

In the wine supply chain, horizontal collaboration is not possible in all stages, particularly in the winemaking stage. This stage corresponds to the winery's core business, and it is under the enologist's strict control, making the wine manufacturing process difficult to replicate outside the company. Consequently, in this paper, we focus on three logistic activities that are standardised across wineries, making them suitable for cooperation under a horizontal collaboration approach. These activities involve the joint planning of transportation, storage, and bottling decisions. Particularly, we focus on the transportation of bulk wine from the fermentation cellars to the bottling plants, the bottling process, the storage of the final product in bottling plants, and the transportation of the final product to ports. Figure 1 depicts an example of the collaborative wine supply chain we consider.

3.1. The collaborative wine supply chain game

In this paper, we model the collaboration among wineries using tools from cooperative game theory and operations research. Particularly, we consider a CFG, in which the characteristic function describes the minimum cost of each coalition's supply chain, and is derived by optimally solving a mixed-integer linear programming model. This model, described in detail in Section 3.2, optimises the wine supply chain, assuming that some resources can be shared between the wineries that form a coalition to collaborate. The CFGs are suitable for cases in which the value of a coalition depends only on its members. This last is a common assumption in the collaborative logistics literature since the operational behaviour of a specific coalition does not generate externalities to the others.

Mathematically, let us define as W the set of players, which in this context refers to wineries. In cooperative game theory, a coalition S corresponds to any nonempty subset of W. The coalition that contains all the players is known as the grand coalition. Let us define the set of all possible coalitions

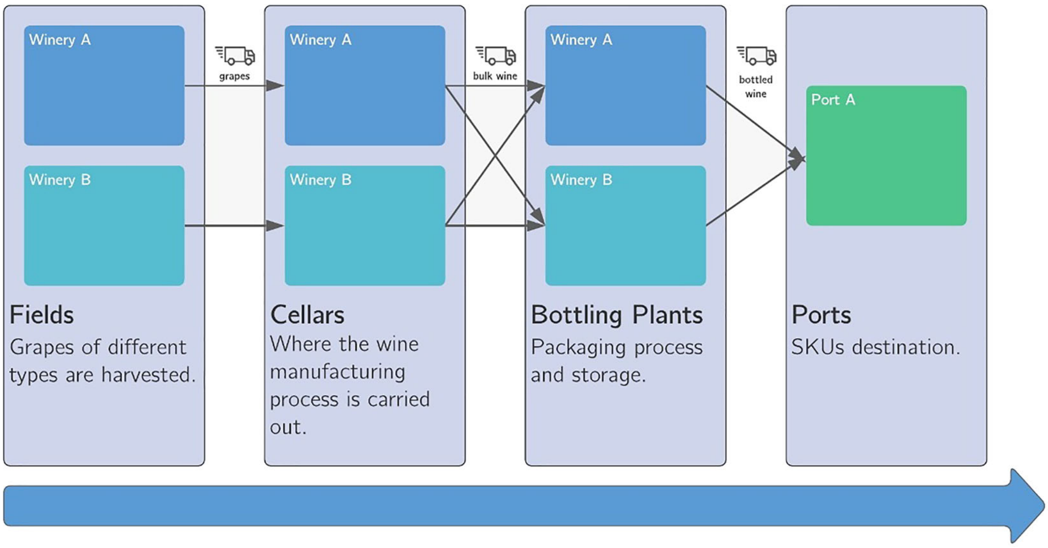

Figure 1. The wine supply chain.

as $\mathcal{K}$. Every coalition $S \in \mathcal{K}$ has an associated cost $C(S)$, which is stored in the characteristic function C denoted by $C : \mathcal{K} \rightarrow \mathbb{R}^+$. In this context, the characteristic function corresponds to the optimal logistical costs that the wineries belonging to the S coalition would have if they collaborated in their production processes. The pair (W, C) is called a transferable cost game. In this kind of game, it is assumed that members can transfer costs/utilities between them. To assess the cost savings and the degree of collaboration, we use three collaboration metrics defined in Section 3.3.1.

When wineries collaborate, they must decide how to allocate the benefits of collaboration among them. This last imposes several challenges, including finding allocations that benefit all firms, creating no incentives for firms to deviate from the collaboration, and guaranteeing that the benefits are shared fairly. A specific rule for determining these payoffs is called a cost allocation method. A desirable property for any cost allocation method is that any member should have incentives to break the coalition. This property is called stability. In this paper, we use four cost sharing methods usually used in the literature (Guajardo & Rönnqvist, 2016). These methods are discussed in Section 3.3.2.

3.2. Computing the characteristic function

3.2.1. Definitions and assumptions

We consider the following assumptions:

- We consider four types of products: grapes, fermenting wine, bulk wine, and bottled wine.
- The grape reception process in the fermentation plants must occur the same day of the harvesting.
- When the grapes arrive at the fermentation tanks, they are made into fermenting wine immediately.
- Fermenting wine becomes finished bulk wine once it has been in the tank for a predefined period.
- Fermenting and finished bulk wine are stored in tanks that have capacities depending on the cellar. Furthermore, a single shared capacity is considered in the cellars, which can be used either for fermenting wine or finished bulk wine.
- Bulk wine can be stored in cellars but not in bottling plants. Thus, bulk wine sent from cellars to bottling plants must be bottled and labelled the same period of the shipment.
- Bottled wine can be held in inventory at the bottling plant.
- All transportation, whether from fields to cellars, from cellars to bottling plants, or from bottling plants to ports, takes the same predetermined time.

3.2.2. Sets

Considers the following sets:

- T: Planning horizon (indexed by t).
- W: Set of wineries (indexed by w).
- I^w: Set of fields of winery w (indexed by i).
- J^w: Set of cellars of winery w (indexed by j).
- K^w: Set of bottling plants of winery w (indexed by k).
- P: Set of destination ports (indexed by p).
- G^w: Set of grape varieties of winery w (indexed by g).
- R^w: Set of bulk wine types of winery w (indexed by r).
- L^w: Set of final bottled wine types of winery w (indexed by l).

If $S \subseteq W$ is a coalition, consider the following sets:

- $I^S = \cup_{w \in S} I^w$
- $J^S = \cup_{w \in S} J^w$

- $K^S = \cup_{w\in S} K^w$
- $G^S = \cup_{w\in S} G^w$
- $R^S = \cup_{w\in S} R^w$
- $L^S = \cup_{w\in S} L^w$

3.2.3. Parameters

The following costs are considered:

- α^w_{igt}: Unit harvesting cost for winery w in field $i \in I^w$ for grapes type $g \in G^w$ during period t of winery $(\$/ton)$.
- μ^w_{ig}: Unit cost for not harvesting at winery w in field $i \in I^w$ grapes of type $g \in G^w$ $(\$/ton)$.
- ρ_{kt}: Unit cost for collaborate at plant k during period t.
- β^w_{jrt}: Unit production cost for winery w in cellar $j \in J^w$ for bulk wine type $r \in R^w$ during period t of $(\$/ton)$.
- γ_{klt}: Unit bottling cost for bottled wine type $l \in L^S$ in bottling plant $k \in K^S$ during period $t \in T$ $(\$/m^3)$.
- δ^w_{ijt}: Unit transportation cost for winery w for any type of grape moved from field $i \in I^w$ to bottling plant $j \in J^w$ during period $t \in T$ $(\$/ton)$.
- ε^w_{jkt}: Unit transportation cost for winery w for any type of bulk wine from cellar $j \in J^w$ to bottling plant $k \in K^S$ during period $t \in T$ $(\$/m^3)$.
- ζ_{kpt}: Unit transportation cost for any type of bottled wine from plant $k \in K^S$ to port $p \in P$ during period $t \in T$ $(\$/m^3)$.
- η^w_{jrt}: Unit holding cost for bulk wine type $r \in R^w$ in the cellar $j \in J^w$ during period $t \in T$ $(\$/m^3)$. This cost arises when bulk wine is kept in tanks for additional periods of time over M_r.
- θ_{klt}: Unit holding cost of bottled wine type $l \in L^S$ in plant $k \in K^S$ during period $t \in T$ $(\$/m^3)$.

The following parameters are considered:

- A^w_{ig}: Takes value 1 if field $i \in I^w$ of winery w has grapes of type $g \in G^w$ and 0 in other cases.
- B^w_{it}: Harvesting capacity of winery w in field $i \in I^w$ during period $t \in T$ (ton).
- C^w_{jt}: Capacity of cellar $j \in J^w$ for winery w during period $t \in T$ (m^3).
- D_{kt}: Bottling capacity at plant $k \in K^S$ during period $t \in T$ (m^3).
- E_{kt}: Inventory capacity at plant $k \in K^S$ during period $t \in T$ (m^3).
- F_{gr}: Quantity of grapes type $g \in G^S$ needed to produce a unit of bulk wine type $r \in R^S$ (ton/m^3).
- V_{ig}: Availability of grapes type $g \in G^w$ at winery w in field $i \in I^w$, where $(i,g) \in \cup_{w\in S} I^w \times G^w$ (ton).
- Q_{rl}: Quantity of bulk wine type $r \in R^S$ needed to produce a unit of bottled wine type $l \in L^S$ (m^3/m^3).
- H_{lpt}: Quantity of bottled wine type $l \in L^S$ required in port $p \in P$ during period $t \in T$ (m^3).
- M_r: Minimum fermentation time required for bulk wine type $r \in R^S$ (weeks).
- N^w_{jr}: Initial inventory of bulk wine type $r \in R^w$ for winery w in cellar $j \in J^w$ (m^3).
- O_{kl}: Initial inventory of bottled wine type $l \in L^S$ at bottling plant $k \in K^S$ (m^3).
- U_{cd}: Transportation time between location c and d, where $(c,d) \in (I \times J) \cup (J \times K) \cup (K \times P)$.

3.2.4. Variables

We consider the following flow variables:

- $x_{gijt} \geq 0$: Quantity of grapes type $g \in G^S$ transported from field $i \in I^S$ to cellar $j \in J^S$ during period t, where $(g,i,j) \in \cup_{w\in S} G^w \times I^w \times J^w$.
- $y_{rjkt} \geq 0$: Quantity of bulk wine type $r \in R^S$ transported from cellar $j \in J^S$ to bottling plant $k \in K^S$ during period t, where $(r,j) \in \cup_{w\in S} R^w \times J^w$.
- $z_{lkpt} \geq 0$: Quantity of bottled wine type $l \in L^S$ transported from bottling plant $k \in K^S$ to port p during period t.

Note that the indexes of the flow variables x_{gijt} are such that $(g,i,j) \in \cup_{w\in S} G^w \times I^w \times J^w$, i.e. only flows belonging to a single winery are considered. Therefore, no transport collaboration is allowed at the harvesting stage, as stated in Section 3.2.1. On the other hand, in the flow variables y_{rjkt} we have $(r,j) \in \cup_{w\in S} R^w \times J^w$, i.e. the bulk wine type r and the fermentation plant j must be from the same winery, but the bottling plant j can belong to any other winery. Thus, the collaboration is incorporated at this stage in the transport from cellars to the bottling plants. Finally, in the flow variables z_{lkpt}, there are no additional constraints on the indexes, allowing the shipment of bottled wine from any bottling plant of the coalition to the ports.

We consider the following production variables:

- $v_{jrt} \geq 0$: Quantity of bulk wine type $r \in R^S$ fermenting in cellar $j \in J^S$ during period t, where $(j,r) \in \cup_{w\in S} J^w \times R^w$.
- $h_{klt} \geq 0$: Quantity of bottled wine type $l \in L^S$ bottled and labelled at the plant $k \in K^S$ during period t.

Note that the indexes of the production variable v_{jrt} are such that $(j,r) \in \cup_{w\in S} J^w \times R^w$, i.e. the bulk wine type r can only be fermented in a cellar j if it belong to the same winery. That is to say, collaboration in the fermentation process is not allowed. On the other hand, in the bottling process, which is represented by the variables h_{klt}, bulk wine from any winery can be bottled and labelled in any bottling plant, thus allowing collaboration.

We consider the following inventory variables:

- $s_{jrt} \geq 0$: Quantity of bulk wine type $r \in R^S$ ready for bottling hold in cellar $j \in J^S$ during period t, where $(j, r) \in \cup_{w\in S} J^w \times R^w$.
- $u_{klt} \geq 0$: Quantity of bottled wine $l \in L^S$ hold at bottling plant $k \in K^S$ during period t.

Note that the indexes of the inventory variables s_{jrt} are such that $(j, r) \in \cup_{w\in S} J^w \times R^w$, which means that the bulk wine to be stored in a cellar of the same winery, thus avoiding collaboration. On the other hand, the inventory variables u_{klt} allow bottled wine from any winery to be held at a bottling plant, thus allowing collaboration.

3.2.5. Objective function

Expression (1) shows the objective function:

$$\begin{aligned}
C(S) = {} & \underbrace{\sum_{t\in T}\sum_{w\in S}\sum_{j\in J^w}\sum_{i\in I^w}\sum_{g\in G^w} \alpha^w_{igt} \cdot x_{gijt}}_{\text{Harvest cost}} + \underbrace{\sum_{w\in S}\sum_{i\in I^w}\sum_{g\in G^w} \mu^w_{ig} \cdot \left(V_{ig} - \sum_{t\in T}\sum_{j\in J^w} x_{gijt} \right)}_{\text{Non harvest cost}} + \underbrace{\sum_{t\in T}\sum_{w\in S}\sum_{j\in J^w}\sum_{i\in I^w}\sum_{g\in G^w} \delta^w_{ijt} \cdot x_{gijt}}_{\substack{\text{Transportation cost from fields}\\ \text{to cellars}}} \\
& + \underbrace{\sum_{t\in T}\sum_{w\in S}\sum_{j\in J^w}\sum_{r\in R^w} \beta^w_{jrt} \cdot v_{jrt}}_{\text{Fermentationcost}} + \underbrace{\sum_{t\in T}\sum_{w\in S}\sum_{j\in J^w}\sum_{r\in R^w} \eta^w_{jrt} \cdot s_{jrt}}_{\text{Inventory cost in cellars}} + \underbrace{\sum_{t\in T}\sum_{w\in S}\sum_{k\in K^S}\sum_{j\in J^w}\sum_{r\in R^w} \varepsilon^w_{jkt} \cdot y_{rjkt}}_{\substack{\text{Transportation cost from cellars}\\ \text{to bottling plants}}} + \underbrace{\sum_{t\in T}\sum_{l\in L^S}\sum_{k\in K^S} \gamma_{klt} \cdot h_{klt}}_{\text{Bottling cost}} \\
& + \underbrace{\sum_{t\in T}\sum_{l\in L^S}\sum_{k\in K^S} \theta_{klt} \cdot u_{klt}}_{\text{Inventory cost at bottling plants}} + \underbrace{\sum_{t\in T}\sum_{p\in P}\sum_{k\in K^S}\sum_{l\in L^S} \zeta_{kpt} \cdot z_{lkpt}}_{\substack{\text{Transportation cost from bottling plants}\\ \text{to ports}}} + \underbrace{\sum_{w\in S}\sum_{t\in T}\sum_{l\in L^w}\sum_{k\in K^S\setminus K^w} \rho_{kt} h_{klt}}_{\text{Transaction cost}}
\end{aligned} \tag{1}$$

3.2.6. Constraints

$$\textstyle\sum_{t\in T}\sum_{j\in J^w} x_{gijt} \leq V_{ig} \qquad \forall w \in S, \forall g \in G^w, \forall i \in I^w \tag{2}$$

$$\textstyle\sum_{j\in J^w} x_{gijt} \leq B^w_{it} \cdot A^w_{ig} \qquad \forall w \in S, \forall g \in G^w, \forall i \in I^w, \forall t \in T \tag{3}$$

$$\textstyle\sum_{i\in I^w : U_{ij}\leq t} x_{gij(t-U_{ij})} = \sum_{r\in R^w} F_{gr} \cdot v_{jrt} \qquad \forall w \in S, \forall j \in J^w, \forall g \in G^w, \forall t \in T : t > \min_{i\in I^w} U_{ij} \tag{4}$$

$$v_{jrt} = 0 \qquad \forall w \in S, \forall j \in J^w, \forall r \in R^w, \forall t \in T : t \leq \min_{i\in I^w} U_{ij} \tag{5}$$

$$\textstyle\sum_{r\in R^w} \displaystyle\sum_{t'>t-M_r}^{t} v_{jrt'} + \sum_{r\in R^w} s_{jrt} \leq C^w_{jt} \qquad \forall w \in S, \forall j \in J^w, \forall t \in T \tag{6}$$

$$s_{jrt} = v_{jrt-M_r} + s_{jrt-1} - \textstyle\sum_{k\in K^S} y_{rjkt} \qquad \forall w \in S, \forall j \in J^w, \forall r \in R^w, \forall t \in T : t > M_r \tag{7}$$

$$s_{jrt} = s_{jrt-1} - \textstyle\sum_{k\in K^S} y_{rjkt} \qquad \forall w \in S, \forall j \in J^w, \forall r \in R^w, \forall t \in T : t \leq M_r \tag{8}$$

$$s_{jr0} = N^w_{jr} \qquad \forall w \in S, \forall j \in J^w, \forall r \in R^w \tag{9}$$

$$\textstyle\sum_{j\in J^w : U_{jk}\leq t} y_{rjk(t-U_{jk})} = \sum_{l\in L^S} Q_{rl} \cdot h_{klt} \qquad \forall w \in S, \forall r \in R^w, \forall k \in K^S, \forall t \in T : t > \min_{j\in J^w} U_{jk} \tag{10}$$

$$h_{klt} = 0 \qquad \forall k \in K^S, \forall l \in L^S, \forall t \in T : t \leq \min_{j\in J^S} U_{jk} \tag{11}$$

$$\textstyle\sum_{l\in L^S} h_{klt} \leq D_{kt} \qquad \forall k \in K^S, \forall t \in T \tag{12}$$

$$u_{klt} = h_{klt} + u_{klt-1} - \textstyle\sum_{p\in P} z_{lkpt} \qquad \forall k \in K^S, \forall l \in L^S, \forall t \in T \tag{13}$$

$$u_{kl0} = O_{kl} \qquad \forall k \in K^S, \forall l \in L^S \tag{14}$$

$$\textstyle\sum_{l\in L^S} u_{klt} \leq E_{kt} \qquad \forall k \in K^S, \forall t \in T \tag{15}$$

$$\textstyle\sum_{k\in K^S : U_{kp}\leq t} z_{lkp(t-U_{kp})} = H_{lpt} \qquad \forall l \in L^S, \forall p \in P, \forall t \in T : t > \min_{k\in K^S} U_{kp} \tag{16}$$

$$x_{gijt} \in \mathbb{R}^+ \qquad \forall t \in T, \forall (g, i, j) \in \cup_{w\in S} G^w \times I^w \times J^w \tag{17}$$

$$y_{rjkt} \in \mathbb{R}^+ \qquad \forall t \in T, \forall k \in K^S, \forall (r, j) \in \cup_{w\in S} R^w \times J^w \tag{18}$$

$$z_{lkpt} \in \mathbb{R}^+ \quad \forall t \in T, \forall l \in L^S, \forall k \in K^S, \forall p \in P \tag{19}$$

$$v_{jrt} \in \mathbb{R}^+ \quad \forall t \in T, \forall (j,r) \in \cup_{w \in S} J^w \times R^w \tag{20}$$

$$h_{klt} \in \mathbb{R}^+ \quad \forall t \in T, \forall l \in L^S, \forall k \in K^S \tag{21}$$

$$s_{jrt} \in \mathbb{R}^+ \quad \forall t \in T, \forall (j,r) \in \cup_{w \in S} J^w \times R^w \tag{22}$$

$$u_{klt} \in \mathbb{R}^+ \quad \forall t \in T, \forall l \in L^S, \forall k \in K^S \tag{23}$$

Constraint (2) forces that the quantity of grapes transported from a field in the whole planning horizon does not exceed the grapes supply. Constraint (3) ensures that the quantity of grapes transported from a field in a given period does not exceed the harvesting capacity of the field. Constraint (4) establishes the balance between the quantity of grapes arriving at each cellar and the amount of bulk wine produced during a specific period. Constraint (5) is a boundary condition on the quantity of fermenting bulk wine. Constraint (6) ensures that the sum of the volume of fermenting bulk wine and finished bulk wine does not exceed the capacity of the cellar. Constraints (7) and (8) represent balance equations for the finished bulk wine inventory in the cellars. Constraint (9) establishes the initial inventory of finished bulk wine in the cellars. Constraint (10) represents the balance between the amount of finished bulk wine arriving at a bottling plant and the amount of bottled wine produced. Constraint (11) corresponds to a boundary condition on the quantity of bottling wine. Constraint (12) ensures that the bottling capacity is respected. Constraint (13) states balance equations for the bottled wine inventory at the bottling plants. Constraint (14) establishes the initial inventory of bottled wine held at the bottling plants. Constraint (15) ensures that the inventory capacity at the bottling plants is respected. Constraint (16) ensures that the demand is satisfied. Finally, Constraints (17)-(23) establish the nature of the variables.

3.3. Post optimal collaboration analyses

Once the characteristic function is computed for all the coalitions, we develop two post-optimal analyses. First, in Section 3.3.1, we assess the benefits of the potential cooperation by introducing three collaboration metrics. Second, in Section 3.3.2, we tackle the problem of cost-sharing by using four well-known allocation methods.

3.3.1. Collaboration metrics

In the computational experiments, three performance measures are considered to quantify the benefits of collaboration, namely the Synergy Value, a metric of the level of collaboration, and a metric of bottling capacity utilisation. First, we define the Synergy Value as the percentage savings from collaborating compared to the sum of costs of working alone (Cruijssen et al., 2007). If we consider that coalition S collaborates, the *synergy value*, $\Theta(S)$, is calculated according to Eq. (24).

$$\Theta(S) = \frac{\sum_{w \in S} C(\{w\}) - C(S)}{\sum_{w \in S} C(\{w\})} \tag{24}$$

Second, the collaboration metric corresponds to the ratio between the amount of wine bottled in other wineries' plants and the total bottled wine processed. If we consider that coalition S collaborates, the collaboration metric, $\Psi(S)$, is calculated according to Eq. (25).

$$\Psi(S) = \frac{\sum_{w \in S} \sum_{t \in T} \sum_{l \in L^w} \sum_{k \in K^S \setminus K^w} h_{klt}}{\sum_{w \in S} \sum_{t \in T} \sum_{l \in L^w} \sum_{k \in K^S} h_{klt}} \tag{25}$$

Third, to demonstrate how the wineries take advantage of the greater efficiencies of the other players in the collaborative scheme, we consider a metric of bottling capacity utilisation. This metric corresponds to the average ratio between the amount of wine bottled and the capacity for each period and plant. If we consider that a winery w collaborates in a coalition S (i.e. $w \in S$), the bottling capacity utilisation metric, $\Omega(w, S)$, is calculated following Eq. (26).

$$\Omega(w, S) = \frac{1}{|T|} \sum_{t \in T} \left(\frac{1}{|K^w|} \sum_{k \in K^w} \sum_{l \in L^S} \frac{h_{klt}}{D_{kt}} \right) \tag{26}$$

3.3.2. Cost-sharing

The model described in Section 3.2 allows computing the optimal cost $C(S)$ for any coalition of wineries S. A relevant property of the characteristic functions is subadditivity, which in mathematical terms can be expressed $C(S \cup T) \leq C(S) + C(T), \forall S, T \in \mathcal{K}$. In our context, it is evident that the characteristic function satisfies the subadditivity property since the solution consisting of optimising S and T separately is feasible for the optimisation problem when considering the coalition $S \cup T$. When the characteristic function satisfies the subadditivity property, the grand coalition minimises the total costs, making it always the best outcome compared to other partitions of players. Consequently, in this research, we do not face a coalition formation problem (Contreras et al., 2020).

Then, it becomes relevant to determine how to share the costs of the players within the grand coalition fairly while ensuring the coalition's stability. In the literature, there are several definitions for stability, including the core (Gillies, 1959), the ε *-core* (Shapley & Shubik, 1966) and the *minmax core* (Drechsel & Kimms, 2010). The best known, and the one we consider in this research, is the core.

To fix ideas, let us call $\pi = (\pi_1, \ldots, \pi_{|W|})$ a cost-sharing vector, i.e. it indicates the cost allocated to each player. The vector π is said to belong to the *core* if it satisfies the properties of efficiency, $\sum_{w \in W} \pi_w = C(W)$, and rationality, $\sum_{w \in S} \pi_w \leq C(S), \forall S \in \mathcal{K}$. When these conditions are satisfied, the cost-sharing vector is said to be stable. In the following, we review four cost-sharing methods we use in this research.

3.3.2.1. *Proportional to stand-alone cost.* The proportional method is a simple cost allocation strategy widely used in the literature. As its name indicates, this method distributes the cost of the grand coalition according to predetermined proportions. Equation 327 shows the formula of this method considering as proportionality factors the quotient between the individual cost of each player with respect to the sum of the stand-alone costs.

$$\pi_w = \frac{C(\{w\})}{\sum_{w \in W} C(\{w\})} C(W) \forall w \in W \tag{27}$$

3.3.2.2. *Shapley value.* The cost assigned to each player through this method corresponds to the average of the player's contributions to coalitions (Shapley, 1953). Equation (28) shows the Shapley value for each player.

$$\pi_w = \sum_{S \subseteq W : w \in S} \left[\frac{(|W| - |S|)!(|S| - 1)!}{|W|!} \right] [C(S) - C(S \setminus \{w\})] \forall w \in W \tag{28}$$

3.3.2.3. *Equal profit method.* The Equal Profit Method (EPM), initially presented in Frisk et al. (2010), corresponds to a cost-sharing method such that the maximum pairwise difference between the relative savings of the players is minimised for cost allocation vectors that belong to the core. Mathematically, let $w \in W$ be a player and π the cost allocation vector. The relative savings of player i with respect to the vector π is $\frac{C(\{w\}) - \pi_w}{C(\{w\})}$. The difference between the relative savings of two players is then $\frac{\pi_w}{C(\{w\})} - \frac{\pi_{w'}}{C(\{w'\})}$. Thus, the EPM is obtained by solving the optimisation problem (29).

$$\begin{aligned} \min \quad & f \\ \text{s.a} \quad & f \geq \frac{\pi_w}{C(\{w\})} - \frac{\pi_{w'}}{C(\{w'\})} \qquad \forall w, w' \in W \\ & \sum_{w \in S} \pi_w \leq C(S) \quad \forall S \subset W \\ & \sum_{w \in W} \pi_w = C(W) \\ & f \in \mathbb{R}, \pi_w \geq 0 \forall w \in W \end{aligned} \tag{29}$$

3.3.2.4. *Nucleolus.* If π is a cost sharing vector and $S \subseteq W$ a coalition, we define the excess of S with respect to the vector π as $C(S) - \sum_{w \in S} \pi_w$, which can be interpreted as a measure of satisfaction of S. As the excess becomes lower, the corresponding coalition has more incentive to refuse that sharing strategy. The nucleolus is a cost-sharing method that ensures all coalitions are as satisfied as possible in terms of the excess measure. Mathematically, the nucleolus is the only vector satisfying $\sum_{w \in W} \pi_w = C(W)$ and $\pi_w \leq C(\{w\}), \forall w \in W$ that lexicographically maximise the excess vector (Schmeidler, 1969).

4. Case study

The Chilean wine industry is a very competitive market, with more than 400 wineries operating in the country, totalling more than 136,000 planted hectares, with a potential production of around 1,200 million litres (ODEPA, 2020). As Figure 2 depicts, plantations and vineyards are mostly concentrated in the centre of the country. In 2020, Chilean wineries produced 1033 million litres, exporting more than 82% of this production for a value of 1825 million US dollars (ODEPA, 2021). This last has placed Chile as the leading *New World* and the fourth overall wine exporter country.[1]

The largest Chilean wineries cooperate under the *Wines of Chile* initiative. This organisation includes 74 wineries and aims to promote the quality and image of Chilean wines.[2] This section conducts a case study focusing on the planning and operation of three wineries in Chile: Concha y Toro, San Pedro de Tarapacá, and Santa Rita. These wineries are members of the *Wines of Chile* initiative, and consequently, they already collaborate, although in limited dimensions, not including the planning and operation. Furthermore, these three wineries are the largest of the Chilean industry. Indeed, in the domestic market, each one of these wineries accounts for about 30% of the wine sold. On the other hand, in the international market, Concha y Toro, San Pedro de Tarapacá and San Rita account for around 31%, 12% and 5% of the Chilean wine sold, respectively. Finally, these three wineries are listed on the stock exchange, and as Chilean monetary authorities require, these companies annually publish reports and income statements to support

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[1] https://www.odepa.gob.cl/rubros/vinos-y-alcoholes

[2] https://www.winesofchile.org/

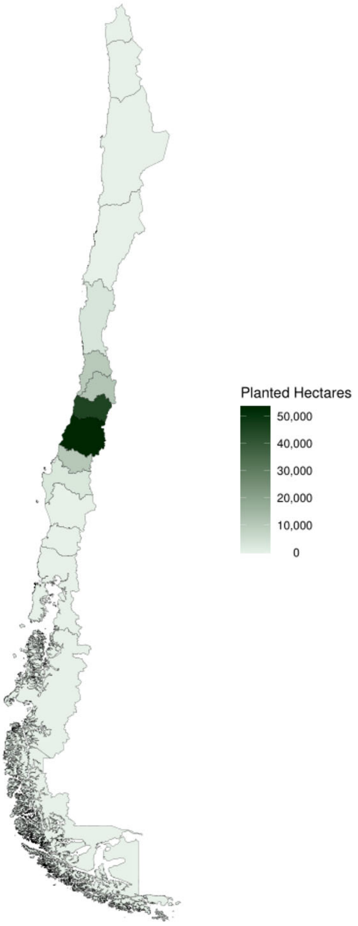


Figure 2. Wine grape plantations. Source: ODEPA (2020).

Table 2. San Pedro de Tarapacá capacities information.

Facility	Fermentation	Bottling	C (m^3)	D^* (m^3/week)
Molina	YES	YES	68,035.00	5,185.60
Isla de Maipo	YES	YES	29,049.00	630.00
San Pedro Cachapoal	YES	NO	900	0.00

* Estimated

Table 3. San Pedro de Tarapacá parameter values.

Parameter	Unit	Value
α^*	M$/ton	517.49
β^*.	M$/$m^3$	644.98
γ^*	M$/$m^3$	161.25
δ^*	M$/ton	113.66
ε^*	M$/$m^3$	32.72
ζ^*	M$/$m^3$	32.72
η^*	M$/$m^3$	161.25
θ^*	M$/$m^3$	161.25
μ^*	M$/ton	0
ρ^*	M$/$m^3$	0
F	ton/m^3	0.75
Q	m^3/m^3	1.00
M^*	weeks	4.00
U_{ij}	weeks	0.00
U_{jk}	weeks	0.00
U_{kp}	weeks	1.00
H^*	m^3	850.00
N^*	m^3	688.00
O^*	m^3	4,301.00
A	weeks	12.00

* Estimated

Table 1. San Pedro de Tarapacá fields information.

Winery	Valley	Area	Estate	Ha. Planted	B^* (Ton)
San Pedro	Valle de Curicó	Molina	Molina	1,056.00	15,840.00
San Pedro	Valle del Maule	Pencahue	Pencahue	742.00	11,130.00
San Pedro	Valle del Cachapoal	Requinoa	Totihue	93.00	1,395.00
San Pedro	Valle del Cachapoal	Requinoa	Quillayes	86.00	1,290.00
San Pedro	Valle de Colchagua	Santa Cruz	Chépica	223.00	3,345.00
San Pedro	Valle del Maipo	Buín	San Ramón	12.00	180.00
San Pedro	Valle del Maipo	Buín	El Tránsito	61.00	915.00
San Pedro	Valle del Cachapoal	Requinoa	Altair	70.00	1,050.00
San Pedro	Valle del Maule	Caliboro	Caliboro	432.00	6,480.00
Santa Helena	Valle de Colchagua	San Fernando	San Fernando	82.00	1,230.00
Santa Helena	Valle de Colchagua	Palmilla	El Huique	329.00	4,935.00
Viñamar	Valle de Casablanca	Casablanca	Casablanca	60.00	900.00
Viñamar	Valle de Casablanca	Casablanca	Loyola	23.00	345.00
Casa Rivas	Valle del Maipo	María Pinto	Santa Teresa	209.00	3,135.00
Leyda	Valle de San Antonio	Leyda	El Maitén	88.00	1,320.00
Leyda	Valle de San Antonio	Leyda	El Granito	75.00	1,125.00

* Estimated

their shareholders' decisions. From these public financial statements, we extract and estimate the necessary information in order to apply the model presented in Section 3.2.

For illustrative purposes, we now present information from San Pedro de Tarapacá winery. Table 1 describes each of San Pedro de Tarapacá's fields, indicating the number of hectares planted and the estimated harvest capacity. Table 2 shows the cellar and bottling capacities, while Table 3 summarises the other parameter values. For the sake of simplicity, we consider only one type of grape, bulk wine, and bottled wine. The weekly demands are estimated proportionally from the total volume produced reported on the annual statements. Appendix A shows the information for the other two wineries.

5. Numerical results

5.1. The impact of collaboration

In this subsection, we analyse the impact of the collaboration between Concha y Toro (cyt), San Pedro de Tarapacá (spt), and Santa Rita (vsr) wineries by applying all the methods described in Section 3.2 to the case study described in Section 4. In particular, Table 4 shows the characteristic function for all the coalitions, which, as expected, satisfies subadditivity.

Table 5 reports the synergy value $\Theta(S)$ and the collaboration metric $\Psi(S)$ for all the coalitions. It can be seen that, as the number of wineries increases, both $\Theta(S)$ and $\Psi(S)$ increase. Consequently, the grand coalition has the highest synergy and collaboration metric values. These results may be explained since, when collaborating, in addition to having greater operational flexibility, there are potential savings associated with the differences in the costs of the different processes in each of the wineries. In other words, wineries characterised by high process costs may benefit from taking advantage of the greater efficiencies offered by the other players in the coalition. Overall, total savings due to collaboration attain 7.69%. This value is lower than other previous papers, in which savings surpass 10% (Frisk et al., 2010; Audy et al., 2011; Basso et al., 2020).

Table 6 shows the metric of bottling capacity utilisation $\Omega(w, S)$ for each winery considering both the stand-alone and grand coalition cases. We can observe a notable difference between the occupation levels under the stand-alone and grand coalition cases. This highly unequal result can be explained mainly by the differences in the costs related to the bottling plants between different wineries. These costs are three: (i) bottling cost, (ii) bottled wine holding cost and (iii) transportation to ports cost. We refer the reader to Table 3 and Appendix A for details. For example, for parameters θ and γ, San Pedro and Santa Rita have costs nearly 30% below those of Concha y Toro. Therefore, coalitions with two wineries containing Concha y Toro can improve efficiency by using these cheaper costs. On the other hand, the $\{vsr, spt\}$ coalition only presents a synergy value of 0.21% because for these wineries, the parameters θ and γ are similar, i.e. the collaboration does not generate significant synergies.

Table 4. Characteristic vector.

Coalition (S)	$C(S)$ (M\$)
{vsr}	266,756.77
{cyt}	1,093,647.07
{spt}	383,558.14
{vsr, cyt}	1,229,041.38
{vsr, spt}	648,974.72
{spt, cyt}	1,331,575.38
{vsr, spt, cyt}	1,566,678.83

Table 5. Results of performance measures.

Coalition	$\Theta(S)$	$\Psi(S)$
{vsr}	0.00%	0.00%
{cyt}	0.00%	0.00%
{spt}	0.00%	0.00%
{vsr, cyt}	9.66%	48.61%
{vsr, spt}	0.21%	53.00%
{cyt, spt}	9.86%	53.48%
{vsr, cyt, spt}	10.17%	69.51%

Table 6. Average occupation status in bottling plants.

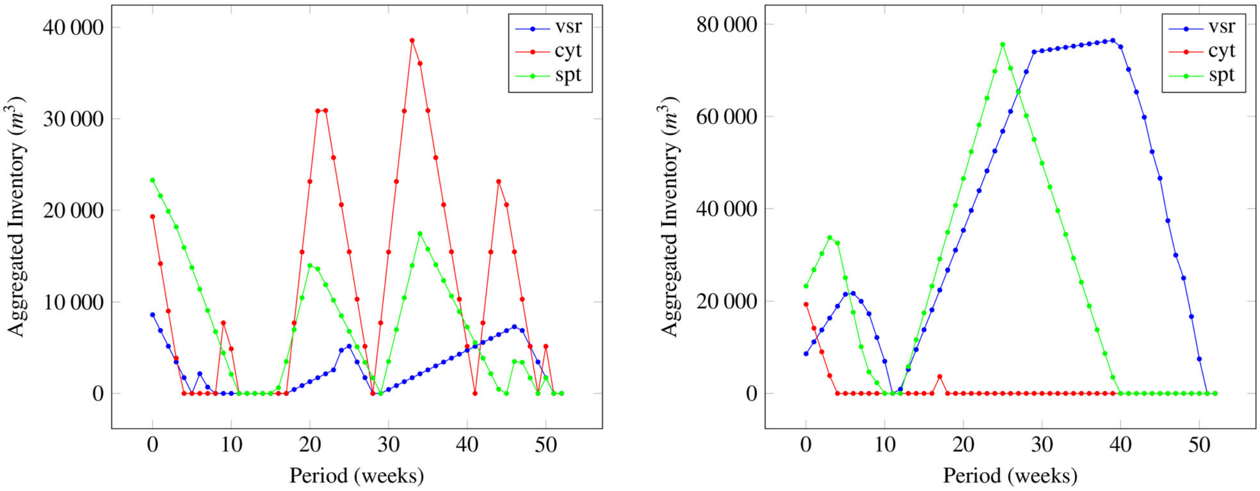
Winery	$\Omega(w, \{w\})$	$\Omega(w, W)$
vsr	35.40%	80.92%
spt	52.92%	37.83%
cyt	36.38%	17.88%

Table 7 presents the costs disaggregated by each process of the wine supply chain. The second column, named Stand-alone, corresponds to the sum of the costs of all wineries working individually. The third column, called Grand coalition, corresponds to the costs of all the wineries working collaboratively. This analysis allows identifying the stages of the wine supply chain where the savings occur. The results show a reduction in the overall inventory costs. This reduction occurs since Concha y Toro reduces its inventory costs (see values of η and θ in Table A.4) by moving as soon as possible their bulk wine to San Pedro's and Santa Rita's bottling plants (Figure 3), incurring in both lower bottling and holding costs. Thus, the main savings are given by inventory being pushed downstream into the wine supply chain from the cellars to the bottling plants. These results could be seen as opposed to the ones reported in Cholette (2009) and Varas et al. (2018) in which postponement of the labelling activities is stated as desirable. However, since our model assumes a deterministic demand, there is no risk of product misallocation.

Table 8 shows the allocated cost using the methods described in Section 3.3.2. In the case of the Shapley Value, the highest percentage savings are obtained by Santa Rita, which means that, within the collaboration, it has the highest average marginal contribution. Conversely, the winery that contributes the least to collaboration is Concha y Toro.

Table 7. Costs disaggregated by processes.

Costs	Stand-alone	Grand coalition	Savings	Savings (%)
Harvest	91,818.40	91,818.40	0.00	0.00%
Transportation from fields to cellars	17,545.16	17,545.16	0.00	0.00%
Fermentation	294,987.70	294,987.70	0.00	0.00%
Inventory at cellars	1,022,677.00	527,060.00	495,617.00	48.46%
Transportation from cellars to bottling plants	10,262.47	10,262.47	0.00	0.00%
Bottling	83,131.80	75,014.20	8,117.60	9.78%
Inventory at bottling plants	211,895.60	537,978.00	−326,08240	−153.89%
Transportation from bottling plants to ports	11,644.28	12,012.90	−368.62	−3.17%
Total	1,743,962.41	1,566,678.83	177,283.58	10.17%



(a) Stand-alone case

(b) Collaborative case

Figure 3. Evolution of aggregated inventory $(\sum_{k,l} u_{klt})$ at plants level. (a) Stand-alone case and (b) Collaborative case.

Table 8. Table of cost sharing in M$.

	Individual	Proportional to individual		Shapley Value		EPM		Nucleolus	
Viña	Cost	Cost	%	Cost	%	Cost	%	Cost	%
vsr	266,756.77	239,639.50	10.17%	234,088.55	12.25%	239,639.50	10.17%	250,930.11	5.90%
cyt	1,093,647.07	982,471.94	10.17%	988,834.03	9.58%	982,471.94	10.17%	955,150.93	12.70%
spt	383,558.14	344,567.38	10.17%	343,756.24	10.38%	344,567.38	10.17%	360,597.80	6.00%

In the case of Nucleolus, when studying the excess vector Table A5, we observe that the coalition $\{cyt, spt\}$ has the lowest associated excess. This implies that this coalition is the most dissatisfied with the Nucleolus. Yet, its excess is positive, and they have no incentive to break the grand coalition due to unequal sharing. The most satisfied coalition corresponds to $\{cyt\}$, which also has the highest percentage savings.

5.2. The impact of transaction costs

Some authors have mentioned that larger coalitions make collaboration more difficult in practice (Flisberg et al., 2015) due to coordination difficulties (Basso et al., 2019). A way to incorporate this remark is to consider another term in the objective function that increases with the number of players in the coalition (Guajardo & Rönnqvist, 2015) or simply limiting the number of players when running the models. In this paper, we take another approach by considering transaction costs, as shown in the last term of Expression (1). For simplicity, we assume each coalition pays these costs proportionally to the total quantity of wine bottled in a different winery. Due to flow conservation constraints, this quantity is a representative metric of the whole collaboration. However, the value of these unit transaction costs ρ_{kt} is challenging to estimate. Thus, in this subsection, we analyse how increasing the values of ρ_{kt} impacts collaboration.

The numerical experiments consist of running the models described in Section 3 using the data described in Section 4 but varying the parameters ρ_{kt}. We consider that all the transaction costs are equal $\rho_{kt} = \rho$, and we vary ρ between 0 to 3000 with a step of 50. For each ρ, we compute $C(W)$, $\Theta(W)$ and $\Psi(W)$, which are plotted in Figure 4(a–c), respectively. From Figure 4(a), we observe that the cost of the grand coalition increases as ρ increases. This last occurs because increasing the transaction costs increase the objective function for the optimisation problem that allows computing $C(W)$, while the constraints for this same problem remain the same. It is worth noting that the shape of the curve is concave, which means that for lower values of ρ, the marginal cost is higher than for larger ρ values. Moreover, as ρ increases, $C(W)$ tends to the sum of the stand-alone costs $\sum_{w \in W} C(\{w\})$, which implies that for values of ρ large enough, the collaboration is no longer relevant. This last remark is also supported by Figure 4(b,c), which shows that for ρ large enough (in our case large than 2500), the synergy value and the collaboration metric are nearly 0%. That is, for ρ large enough, the collaboration and its benefits vanish. It is worth noting that, in any collaborative game, an increase in the transaction costs should have a similar effect, reducing the likelihood of the collaboration.

5.3. Sensitivity analysis

In this paper, we estimate the model's parameters using data gathered from wineries' financial

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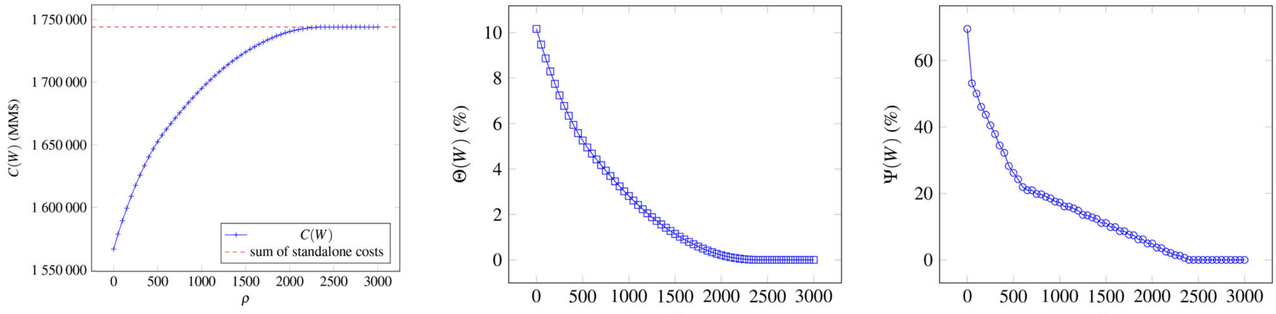

(a) The characteristic function of the grand coalition $C(W)$ versus ρ

(b) The synergy value $\Theta(W)$ versus ρ

(c) The collaboration metric $\Psi(W)$ versus ρ

Figure 4. Experimental results for different transaction cost values. (a) The characteristic function of the grand coalition $C(W)$ versus ρ; (b) The synergy value $\Theta(W)$ versus ρ; and (c) The collaboration metric $\Psi(W)$ versus ρ.

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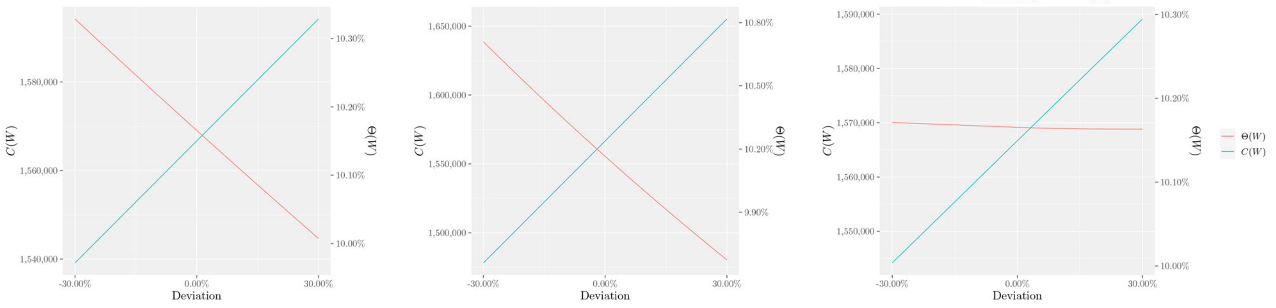
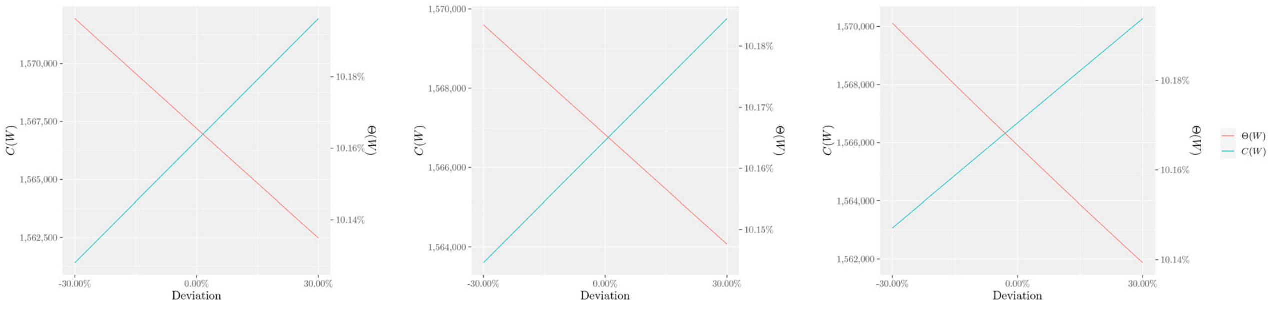


(a) Unit harvesting cost α.

(b) Unit production at cellars β.

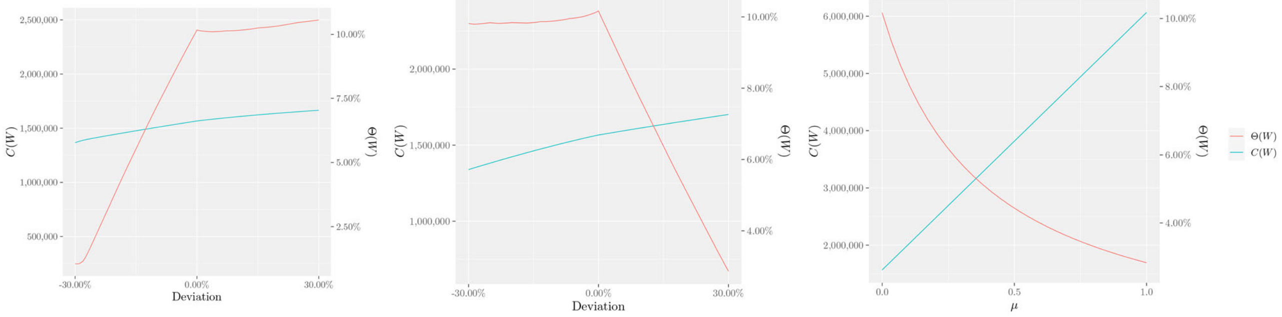
(c) Unit bottling cost γ.



(d) Unit transportation cost field-cellar δ.

(e) Unit transportation cost cellar-bottling ε.

(f) Unit transportation cost bottling-port ζ.



(g) Unit holding cost at cellars η.

(h) Unit holding cost at plant θ.

(i) Unit cost for not harvesting μ.

Figure 5. Sensitivity analysis of the costs' parameters. (a) Unit harvesting cost α; (b) Unit production at cellars β; (c) Unit bottling cost γ; (d) Unit transportation cost field-cellar δ; (e) Unit transportation cost cellar-bottling ε; (f) Unit transportation cost bottling-port ζ; (g) Unit holding cost at cellars η; (h) Unit holding cost at plant θ; and (i) Unit cost for not harvesting μ.

statements prepared using estimates, judgements, and assumptions (Varas et al., 2021). Thus, the reported values are prone to change, and consequently, the estimated parameters might be slightly different. So, in this subsection, we conduct a sensitivity analysis to study whether the results presented in Sections 5.1 and 5.2 change when the costs parameters are subject to variations.

The sensitivity analysis works as follows. For each one of the following parameters: α, β, γ, δ, ε, ζ, η, and θ, we perturb their values between −30% and +30% compared to the ones of the case study (see Table A4). For μ, on the other hand, we choose a different setup. Since both its original value is set to zero and only non-negative values are of interest, we perturb this parameter only from 0% to 30%.

For each considered value, we recorded the characteristic function C and the synergy value Θ for the grand coalition W. Figure 5 depicts our numerical results.

As a general remark, we can mention that $C(W)$ is a linear function except in the cases shown in Figure 5(g,h), which, instead, are piece-wise linear functions. This linearity is not surprising since the objective function shown in Expression 31 is linear with respect to the costs' parameters. Yet, it is interesting to point out that the exceptional cases correspond to η and θ, which are the costs of the logistics processes that lead to the collaboration savings (inventory at cellars and the bottling plants). We analyse the results in more detail now.

The computational experiments show different results depending on the perturbed cost. For the parameters α, β, γ, δ, ε and ζ, the changes are minimum. The characteristic function always falls in an interval ranging between M$1,450,000 and M$1,650,000, while the synergy value always falls in the interval between 10.00% and 10.30%. These results are in line with Table 7 in which the processes associated with these costs does not generate relevant collaborative savings. On the other hand, the changes are relevant for the parameters η and θ. The characteristic function always falls in an interval ranging between M$0 and M$2,500,000, while the synergy value always falls in the interval between 1.00% and 11.00%. For μ, the analysis is somewhat different because we consider nominal variations instead of % variations. In this case, we find that the synergy value decreases as the value of μ increases. This last occurs because μ does not impact the collaboration; thus, the numerator in equation 324 remains fixed, but the denominator increases.

Special attention is needed for Figure 5(g,h) in which a mirror effect is perceived for the synergy value. For values of η smaller than the nominal one, the synergy value drops sharply. To explain this reduction, the reader should recall that in the Chilean case study, η and θ are equal within each winery but different between wineries (Table A4). In fact, as stated in Section 5.1, the main savings are given by inventory being pushed downstream into the wine supply chain from the cellars to the bottling plants, from Concha y Toro to the other ones. Thus, if η diminishes, the relative difference between the unit holding costs at cellars and bottling plants decreases, reducing the value of collaboration considerably. An analogous analysis occurs when θ increases (right half of Figure 5(h)). When η increases compared to the baseline, the outcome is less obvious because both the stand-alone and the grand coalition objective functions increase, leading to a trade-off. Even though the synergy value has some fluctuations for positive deviations of η (and for negative deviation θ), these are small. Overall, these analyses confirm that collaboration savings are enhanced when players have different cost structures.

6. Concluding remarks

This paper studies the impact of horizontal collaboration in the wine supply chain. For this purpose, we model collaboration as a cooperative game with transferable costs. The characteristic function is obtained from the solution of a mixed-integer linear programming model that allows optimising the performance of this chain. The benefits of collaboration are addressed by developing a case study that considers three of the largest exporting wineries in Chile. Our results show that horizontal collaboration reduces operational costs up to 10.17%, which may make a difference in this hypercompetitive industry. The reduction of bulk wine inventory cost produces the most significant savings. Since the subadditivity property holds, the grand coalition provides the most benefits. Thus, we address the cost-sharing problem using well-known splitting methodologies.

In this paper, we have addressed different gaps observed in the literature. First, we study the collaborative wine supply chain planning using operations research and cooperative game theory tools. To the best of our knowledge, this is the first contribution that combines both approaches to improve the performance of the whole supply chain in the wine industry. Second, we formulate a novel optimisation model to handle collaboration and optimise different logistic activities. The formulation has several distinctive features. On the one hand, our formulation incorporates the time the grapes must remain in the fermentation tanks to obtain wine in bulk, allowing us to define the duration of the winemaking process for each type of product. On the other hand, both fermenting and fermented wines use the same cellars' capacity, reflecting more realistically the competition for the use of scarce resources. Third, this work provides evidence to the literature on the benefits of horizontal collaboration in a real environment using realistic data from the Chilean wine industry. At the same time, we contribute to horizontal collaboration literature by considering transaction (or moral) costs when computing the characteristic function, making our study more realistic.

Managers can use the methodology proposed in this paper to identify the most proper way to collaborate in supply chain wine planning. Our paper recognises a cost-saving opportunity by taking advantage of the cost differences between logistic activities. For the Chilean case, the main cost savings comes from inventory being pushed downstream from the cellars to the bottling plants. This fast bottling strategy implies that the maximum level of inventory doubles at bottling plants compared to the non-collaborative case. Note, however, that this increase requires spare inventory capacity at the bottling plants, which may not be available in the short-term. Consequently, the implementation of a collaborative strategy could guide strategic decisions –such as the facility location and sizing problem– by identifying opportunities based on cost differentials. Additionally, although our formulation does not address the coalition formation problem, it could be easily extended in that direction, providing support to firms looking for suitable collaboration partners.

However, the results presented in this paper have to be considered carefully. First, we introduce transaction costs to proxy the fact that larger coalitions are less likely to arise in practice due to coordination difficulties. Nevertheless, these costs might be difficult to estimate in practice, especially before the collaboration occurs, since they include not only monetary but also non-monetary costs (Jindal & Kerr, 2007). This last is especially relevant since very high transaction costs can make the collaboration undesirable. Second, while our results show significant cost reductions when the wine supply chain is planned in a coordinated manner, a collaborative strategy of this level would require a high level of operational coordination. In this regard, planning and operational issues seem to be one the main deterrent to practical implementations of horizontal collaboration in logistics (Basso et al., 2019). Therefore, more limited collaborative strategies could serve as a starting point for wineries to build the necessary trust.

Different future research lines follow from this paper. First, based on one of the issues discussed above, it is interesting to study collaborative models in limited settings, for example, in specific stages of the supply chain. An example of this could be the sharing of expensive resources such as fermenting tanks and cellars during the wine production stage. Second, since horizontal collaboration success is based on trust, it is essential to ensure the stability of the relationship in the long term (Pomponi et al., 2015). However, climate change poses a challenge to wineries around the world by increasing the uncertainty in different processes, including the harvest dates and grape quality (De Orduna, 2010). Thus, an interesting research line is to study the coalition structure problem in the wine industry under cost uncertainty. Tackling this problem requires the use of specialised approaches, such as stochastic programming or robust optimisation.

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Appendix A: Wineries Information

Table A1. Information of Concha y Toro's facilities.

Valley	Ha. production	Ha. developed	Total Ha. planted	B* (Ton)
Limarí	1,008.00	264.00	1,272.00	19,080.00
Casablanca	267.00	0.00	267.00	4,005.00
Aconcagua	97.00	0.00	97.00	1,455.00
Leyda	112.00	0.00	112.00	1,680.00
Maipo	605.00	94.00	699.00	10,485.00
Cachapoal	1,670.00	147.00	1,817.00	27,255.00
Colchagua	2,165.00	247.00	2,412.00	36,180.00
Curicó	678.00	67.00	745.00	11,175.00
Maule	2,272.00	582.00	2,854.00	42,810.00
Bío-Bío	0.00	170.00	170.00	2,550.00

* Estimated

Table A2. Information of Santa Rita's facilities.

Estate	Valley	Ha. Planted	Total Ha.	B* (Ton)
Punitaqui	Limarí	109.50	488.00	7,320.00
Casablanca	Casablanca	115.38	266.00	3,990.00
Casablanca	Casablanca	199.00	245.00	3,675.00
Leyda	SanAntonio	90.00	95.00	1,425.00
Buin	Maipo	559.41	3,012.00	45,180.00
Pirque	Maipo	133.00	371.00	5,565.00
Alhué	Maipo	350.30	5,133.00	76,995.00
LosLirios	Rapel	0.00	10.00	150.00
Peralillo	Palmilla	322.02	377.00	5,655.00
Pumanque	Rapel	669.19	1,169.00	17,535.00
Apalta	Rapel	77.00	100.00	1,500.00
Apalta	Rapel	40.00	40.00	600.00
RíoClaro	Curicó	185.48	229.00	3,435.00
Itahue	Curicó	273.00	301.00	4,515.00
Cauquenes	Maule	128.33	276.52	4,147.80

* Estimated

Table A3. Summary of cellars facilities.

Winery	Cellars Plants	Cap. vinification (C*)
Santa Rita	Buin	12,068.00
	Los Lirios	12,068.00
	Lontué	12,068.00
	Palmilla	12,068.00
	Carmen	12,068.00
	Río Claro	12,068.00
Concha y Toro	–	18,059.00
	–	18,059.00
	–	18,059.00
	–	18,059.00
	–	18,059.00
	–	18,059.00
	–	18,059.00
	–	18,059.00
	–	18,059.00
	–	18,059.00
	–	18,059.00
	–	18,059.00
San Pedro de Tarapacá	Molina	68,035.00
	Isla de Maipo	29,029.00
	San Pedro Cachapoal	900.00

* Estimated

Table A4. Summary of winery parameters.

Parameter*	Unit	Value		
		spt	cyt	vsr
α	M\$/ton	517.49	238.03	333.55
β	M\$/m^3	644.98	904.80	641.91
γ	M\$/m^3	161.25	226.20	160.48
δ	M\$/ton	113.66	43.56	50.64
ε	M\$/m^3	32.72	21.83	23.09
ζ	M\$/m^3	32.72	21.83	23.09
η	M\$/m^3	161.25	226.20	160.48
θ	M\$/m^3	161.25	226.20	160.48
F	ton/m^3	0.75	0.75	0.75
Q	m^3/m^3	1.00	1.00	1.00
M	weeks	4.00	4.00	4.00
H	m^3	850.00	2,575.00	860.00
N	m^3	688.00	3,089.00	688.00
O	m^3	4,301.00	6,436.00	4,301.00
A	weeks	12.00	12.00	12.00

* Estimated

Table A5. Coalition excess vector for nucleolus.

Coalition	{cyt,spt}	{vsr}	{spt}	{vsr,cyt}	{vsr,spt}	{cyt}
Excess	14,539.00	14,539.00	21,439.00	21,439.00	34,691.00	122,279.00.