Coalitions in collaborative forest transportation across multiple areas

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Abstract. We study a problem of collaboration in the transportation of forest biomass in Sweden. The country is divided in different areas. While some companies operate in a single area, other companies operate in two or more areas. With different coalitions forming in different areas, a same company may belong to two or more coalitions. In this article, we develop three approaches for this problem, based on integer programming models. We compare the solution to these approaches using real-world data. Our results reveal that, although the area division restricts supply points to fulfil only demand points within their corresponding area, it renders flexibility when there is a bound limiting the cardinality of the coalitions.

Keywords: Collaborative logistics; Forest transportation; Coalition configuration; Coalition structure; Game theory.

1 Introduction

Collaborative transportation among different companies has received increasing attention in recent years, driven mainly by cost and environmental concerns. Most of the literature on collaborative transportation has focused on how the companies should split the costs, as reviewed in a recent survey by [1]. Splitting costs is an important problem, but usually assumes as given which companies take part in the collaboration. A primary problem relates to the formation of the coalitions. This problem has received much less attention in the transportation literature. Related articles are [2] and [3]. The former studies how the synergy varies according to different characteristics of partner companies. The latter studies a coalition structure problem which consists of partitioning the set of companies into disjoint sets. In this article, we study a problem in which a same company can eventually collaborate in more than one coalition. Our motivation comes from a real world case involving 29 companies in the forest biomass industry in Sweden. Some companies in this industry have operations in the whole country or across large regions, while some others have operations in smaller regions. It is naturally expected that the larger companies can collaborate in several coalitions formed in different areas of the country. For this situation, we study and compare three approaches. In one approach, the country is divided in five areas beforehand and we find the best coalition structure within each area independent from each other. The coalitions within each area must respect an upper bound on cardinality. In a second approach, we further introduce an upper bound on the total number of partners at national level for each company, so that the best coalition structures within the areas must be found simultaneously. In a third approach, we omit the area division and study the problem at national level. We formulate and solve integer programming models for each of these approaches and then compare their solutions.

2 Background and problem description

Forest transportation has been a fruitful venue for recent research in collaborative logistics ([3], [4], [5], [6], [7]). It often happens that different companies need to perform transport operations from harvesting points to demand terminals across similar areas. This provides opportunities for the companies to collaborate with each other. The collaboration can occur, for example, by bartering. This means that companies exchange

the tasks of fulfilling a demand point from each others' supply points. The collaboration can also occur by backhauling, which combines the supply and demand points of different companies in a same route. This often reduces the empty miles travelled by the trucks performing the transports. For example, suppose a company requires a transport from supply point i to demand point j. In parallel, another company has a supply point at j or nearby, and a demand point at i or nearby. A backhauling route in collaboration can take advantage of a same truck to deliver the load of the first company from i to j and, instead of coming back empty to i, pick up the loads of the second company near j and deliver them to the point near i. A collaborative plan usually renders savings to the companies. Also, the reduction of total travelled distance implies less emissions, so collaboration is also a way to encourage green logistics.
Most literature in collaborative logistics and cooperative game theory has focused in problems where a single company is an indivisible unit and it must belong to only one coalition. This notion might not necessarily fit a situation where some of the companies operate over a large geographical territory (say a whole country) and some others focus in just one or few areas. Companies covering a large territory may act by area divisions, to become part of different coalitions in different areas. This is important even if the grand coalition in the whole territory represents the lowest cost alternative, because as the number of partners grows coordinating the cooperation becomes more problematic and/or costly [8].
Our aim in this article is to find the *best* coalitions in a territory divided in several areas, considering bounds in the cardinality of the coalitions and that eventually a same company may integrate different coalition in different areas. Here, *best* refers to a solution that minimizes the total transportation cost from an overall perspective. The resulting problem combines aspects of three different problems: transportation planning, coalition structure and coalition configuration. We briefly describe these problems below.

2.1 Transportation planning

A company has points of supply and demand for a single commodity, spread over different geographical locations. The supply quantity at each supply point is limited. The demand quantity at each demand point must be fulfilled. There is a unitary cost of transportation from each supply to demand point. The transportation planning problem consists of finding the flows that minimize the total cost of fulfilling demand from the supply points. This transportation problem is well-known in the literature since early times [9]. Several variations, adding more aspects into the problem (such as multiple commodities or inventory alternatives) can also be found in the literature. We in particularly refer to [10] for a complete description of an optimization model used in practice for forest biomass logistics which will be relevant for our case study.
In a non-collaborative solution, every company performs its plan separately from the rest. In a collaborative solution, different companies can perform joint plans. The structure of the problem in this case remains the same, but simply allowing supply points from one company to deliver flow at demand points from another companies. The collaborative solution is at least as good as the non-collaborative solution. This is easy to see because the solution to the non-collaborative problem is feasible in the collaborative problem, so in the worst case the solution to the latter will be the same as the solution to the former. In practice, it usually happens that the solution to the collaborative problem is strictly better. The optimal objective value to the transportation planning for a coalition k, gives the characteristic function value for such a coalition, that we will denote by C_k.

2.2 Coalition structure

A coalition structure is a partition of the set of players, that is, a collection of disjoint sets whose union equals the original set of players [11]. Its definition comes from the game theory literature and its first apparitions in collaborative transportation are [3] and [7]. We are particularly interested in finding a coalition structure that minimizes the total cost, subject to a cardinality constraint bounding the maximum number of players within a coalition.

2.3 Coalition configuration

Given an original set of players, a coalition configuration is a collection of subsets, not necessarily disjoint, whose union equals the original set of players [12]. Its definition comes from the game theory literature and, to our knowledge, it has not been studied in collaborative transportation. We are interested in finding a coalition configuration that minimizes the total cost, subject to a cardinality constraint bounding the maximum number of players within a coalition.

3 Models

In this section, we formulate integer programming models aimed at identifying the coalitions that minimize total costs under three different approaches. Before describing them, we introduce some notation.

Sets and parameters
N : set of companies.
A : set of areas.
N_a : set of companies with operations in area a.
m: upper bound on the cardinality of the coalitions.
K_m : set of all coalitions of cardinality less or equal than m.
$\mathscr{K}_{am}$: set of all coalitions that belong to area a and whose cardinality is less or equal than m.
C_k: optimal cost of coalition k (that is, the cost of the optimal transportation plan of k acting as coalition).
$\alpha_{i,k}$: binary parameter equal to 1 if company i belongs to coalition k, zero otherwise.

3.1 Approach 1: Coalitions within each area

In this first approach, we formulate a coalition structure problem within each area independently from each other, in which the formed coalitions must respect a cardinality upper bound. For a generic area a and upper bound m, we formulate an integer linear programming model in the binary variables $z_{a,k}$ as follows:

$$[P_{am}] \qquad \min \sum_{k \in \mathscr{K}_{am}} C_k \cdot z_{a,k} \tag{1}$$

$$\sum_{k \in K_m} \alpha_{i,k} \cdot z_{a,k} = 1 \quad \forall i \in N_a \tag{2}$$

$$z_{a,k} \in \{0,1\} \; \forall k \in \mathscr{K}_{am} \tag{3}$$

In $[P_{am}]$, variable $z_{a,k}$ takes the value 1 if coalition k is selected within the partition of area a and zero otherwise. The variable is defined for all coalition k such that it belongs to area a and its cardinality is less or equal than m. The objective function (1) minimizes the total cost of the partition within the corresponding area a. Constraints (2) require that each player with presence in area a must belong to exactly one set in the partition. Thus, $[P_{am}]$ is a set partitioning model where the cardinality of its sets is bounded by m. The overall solution that results from solving $[P_{am}]$ for all area a, provides a coalition configuration for the whole territory.

3.2 Approach 2: Coalitions within each area with restricted total number of partners

In this second approach, we formulate a coalition structure problem within each area, in which the formed coalitions must respect a cardinality upper bound, as well as we did in the first approach. However, we now also introduce an upper bound b_i indicating the maximum total number of players that company i can collaborate with. This leads us to formulate a single integer linear programming model for the territory involving all areas, as follows:

$$[PA_m] \qquad \min \sum_{a \in A} \sum_{k \in \mathscr{K}_{am}} C_k \cdot z_{a,k} \tag{4}$$

$$\sum_{k \in K_m} \alpha_{i,k} \cdot z_{a,k} = 1 \quad \forall a \in A, i \in N_a \tag{5}$$

$$\sum_{j \in N: j \neq i} w_{i,j} \leq b_i \quad \forall i \in N \tag{6}$$

$$\sum_{a \in A} \sum_{k \in \mathscr{K}_{am}} \alpha_{i,k} \cdot \alpha_{j,k} \cdot z_{a,k} \leq |A| \cdot w_{i,j} \quad \forall i \in N, j \in N : i \neq j \tag{7}$$

$$w_{i,j} \leq \sum_{a \in A} \sum_{k \in \mathscr{K}_{am}} \alpha_{i,k} \cdot \alpha_{j,k} \cdot z_{a,k} \quad \forall i \in N, j \in N : i \neq j \tag{8}$$

$$z_{a,k} \in \{0,1\} \; \forall a \in A, k \in \mathscr{K}_{am}; \;\; w_{i,j} \in \{0,1\} \; \forall i \in N, j \in N : i \neq j \tag{9}$$

In $[PA_m]$, the definition of variables $z_{a,k}$ remains the same as in $[P_{am}]$, but note now all of them are part of a same model. Variable $w_{i,j}$ takes the value 1 if companies i and j are part of a same coalition in at least one area, and zero otherwise. The objective function (4) minimizes the total cost of the configuration. Constraints (5) require that each player with presence in area a must belong to exactly one coalition in area a. Constraints (6) impose the upper bound in the total number of collaborators for each company. Constraints (7)-(8) establish logical relationships to calculate variables $w_{i,j}$.
As well as $[P_{am}]$, problem $[PA_m]$ results in a partition within each area where the cardinality of its sets are bounded by m, but also in a coalition configuration for the whole territory.

3.3 Approach 3: Coalitions in the overall territory

In this third approach, we ignore the area definition and address the whole territory as a single area. We keep, however, the cardinality bound m.

$$[P_m] \qquad \min \sum_{k \in K_m} C_k \cdot z_k \tag{10}$$

$$\sum_{k \in K_m} \alpha_{i,k} \cdot z_k = 1 \quad \forall i \in N \tag{11}$$

$$z_k \in \{0,1\} \; \forall k \in K_m \tag{12}$$

In $[P_m]$, the meaning of variables, objective function and constraints remains the same as in $[P_{am}]$. We have simply dropped the index a. Thus, we have a single set partitioning model in which the sets in the partition respect the upper bound m. Unlike $[P_{am}]$ and $[PA_m]$, this third approach provides only a coalition structure (overlapping coalitions are not allowed), because each company is part of exactly one coalition.

4 Case study

In this section, we apply the previous approaches in a country-wide study in forest fuel transportation involving 29 companies in Sweden. Forest fuels are an important bioenergy assortment, which account for about 14% of the biofuels or about 4% of Sweden's total energy. There are large volumes of forest fuel available in the Swedish forest. However, it is a low-value commodity and it is very sensitive to logistic cost to make it profitable. Thus, efficient transportation is crucial to make forest fuels a competitive source of bioenergy. By using optimization models and a decision support system, [6] studied alternatives to lower the costs in a case that accounts for all forest fuel transport operations in Sweden. The case involves 200,000 transports of about 6.1 million tons of forest biomass, equivalent to 17.4 TWh of energy consumption. The study found potential savings of about 22%, where 12% are due to collaborative transportation. The impact of collaborative transportation in this case does not only account for the savings the companies can achieve but also for reducing emissions from the trucks and increasing the use of bioenergy. The savings are computed over the basis that all coalitions collaborate in the grand coalition. As previously mentioned though, collaborative transportation in practice tends to involve coalitions with a limited number of companies. In this article, we limit ourselves to coalitions whose cardinality is at most $m = 4$. This also helps to cope with the high dimension involved in our case, where there are potentially $2^{29} \approx 536$ million coalitions. The computation of C_k for each of these coalition involves solving a transportation planning problem, whose dimension ranges from 700 thousand variables and 120 thousand constraints to 100 million variables and 1.2 million constraints. The corresponding solution times are between 30 seconds

and 30 minutes. To solve the underlying problem for each instance we use the decision support system FuelOpt described in [10].
We implement the integer programming models of Section 3 in AMPL and solve them using the solver CPLEX. For approaches 1 and 2, the country is divided in 5 areas according to geographical criteria. The number of companies in each area ranges from 6 to 16, as can be seen in the second column of Table 1. The

Table 1: Results (cost in million SEK) per area of the non-collaborative approach and the collaborative approaches 1 and 2.

Area ID	# Companies	Non-collaborative	Approach 1		Approach 2	
NN	6	75.4	73.2	3.0 %	74.5	1.2 %
SW	9	98.4	93.1	5.4 %	93.1	5.4 %
SE	11	118.6	110.4	6.9 %	110.9	6.5 %
MD	15	176.8	166.2	6.0 %	168.2	4.9 %
SN	16	72.7	66.2	8.9 %	67.8	6.8 %
Total		541.9	509.0	6.1 %	514.4	5.1 %

third column of Table 1 shows the total cost of the non-collaborative solution (that is, the sum of the stand-alone costs). The first approach provides the highest savings, in total, of 6.1% or about SEK 32.9 million in comparison to the non-collaborative solution. The second approach provides relatively lower savings, but still important with respect to the non-collaborative solution, in the order of 5.1% equivalent to SEK 27.5 million. Note the results of approach 2 depends on the upper bound b_i limiting the total number of partners per company in constraints (6). The results in Table 1 are those obtained when using $b_i = 4\ \forall i \in N$. Figure 1 shows the results for this and other values of b_i, ranging from 0 to 15. When $b_i = 0$, no collaboration occurs

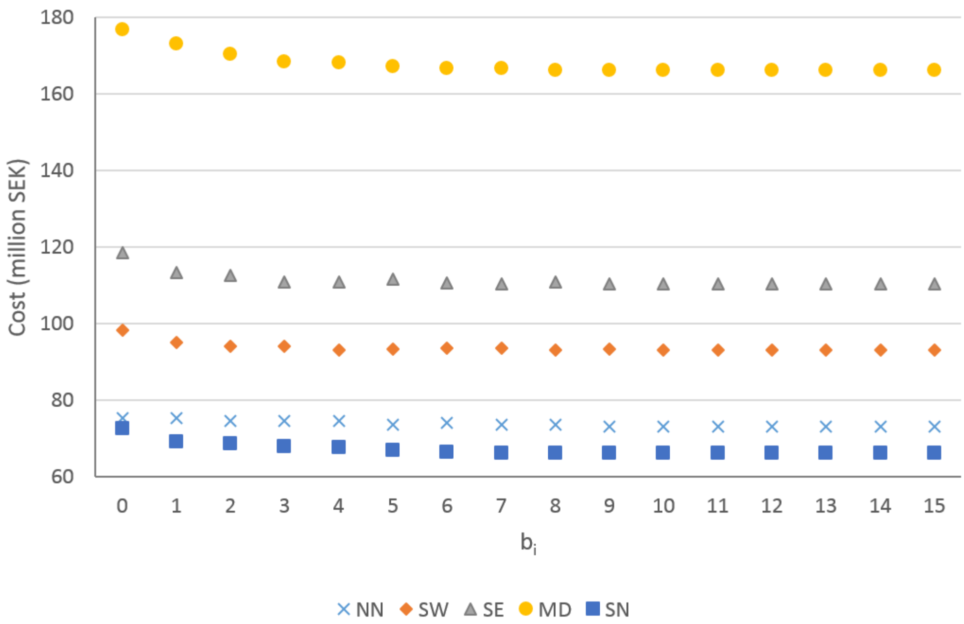

Figure 1: Cost per area as function of the upper bound b_i on the maximum number of partners per company

and the costs are equal to the sum of the stand-alone costs. Incrementing b_i relaxes model $[PAm]$ which is reflected in the reduction of the cost achieved by approach 2. This reduction occurs up to $b_i = 10$, where the cost provided by approach 2 equals the cost provided by approach 1. After then, the increment in b_j has no more impact.
As for the approach 3, where the area concept is omitted, the total cost obtained is SEK 510 million. This represents savings of SEK 31.3 million with respect to the non-collaborative solution, equivalent to 5.8%. Note the cost obtained by approach 3 is higher than the cost obtained by approach 1 by SEK 1.6 million. We find this interesting, because it means that the area divisions in approach 1 renders some flexibility to the companies with presence in more than one area. Since the upper bound m takes place in the solution to each of the areas independent from the others, in approach 1 a company may end up collaborating with

up to $|A| \cdot (m-1)$ partners. In contrast, in approach 3 a company may collaborate with up to only $m-1$ partners. Note approach 3 is better in terms of the transportation planning problem, because it allows any supply point to deliver to any demand point within a coalition, while in approach 1 these are limited by the area segmentation so that the a supply point in one area cannot supply a demand point in another area. However, this advantage of approach 3 is not enough to overwhelm the flexibility rendered by using the upper bound m at area level instead of the whole country level. Likewise, approach 2 achieves a lower cost than approach 3 for any value of b_i between 7 and 15. Note the comparison is done by using the same value $m = 4$ in all approaches. A sufficiently large value of m would normally lead to achieve the best result with approach 1. However, as previously mentioned, establishing collaboration in practice is usually limited in the number of partners.

5 Concluding remarks

This article studied a problem of collaborative transportation in which a same company may be part of different coalitions in different areas. The possibility of companies belonging to more than one coalition relates to what in cooperative game theory is known as coalition configuration. This article is, to our knowledge, the first one studying the coalition configuration problem in the context of collaborative transportation. We studied and compared three approaches. The three approaches are based on integer programming models, which use as input the cost of the optimal transportation plan of each allowed coalition. Despite the area division restricts all supply points within one area to fulfil demand of points within the same area, we have found the area division renders flexibility when the collaboration is restricted to a bound in the cardinality of the coalitions. This is reflected in that approaches 1 and 2, both affected by the area division, achieved higher savings than the approach 3. While this depends on the particular bound used to limit the cardinality, it sheds some lights in that the collaboration restricted to areas may serve as solution in cases where a large territory makes impractical to establish cooperation among so many different companies.
Our article opens several directions for further research. One refers to how to allocate the cost among the companies within each coalition. Different methods may affect the final outcome for each company, which might eventually lead some companies are more or less benefited from the area division. Another interesting problem is related to how to design the areas, which might have an important effect in the potential for collaboration.

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