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A Horizontal Collaborative Approach based on Shapley Value in the Supply Chain Distribution

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Abstract. This paper addresses the problem of horizontal collaboration between carriers at the tactical planning level of the supply chain distribution. The study focuses on the relationship between a shipper and many carriers used to serve the transport requests of several geographically distributed customers. A profit sharing mechanism based on game theory is proposed in order to implement win-win collaboration between the carriers. The Shapley value is used to fairly share the profit of the grand coalition between the carriers. The collaboration is supported by mixed-integer linear programming model for the transport planning of all possible coalitions of carriers.

Keywords: distribution, planning, collaboration, game theory, mixed integer linear programming

1. Introduction

The majority of companies nowadays agree that an optimized supply chain is necessary to increase profit and market share. Among the supply chain functions, the transport plays a central role in seamless supply chain operations. This function clearly appears as a crucial element to get an efficient global performance of this supply chain. The key decision levels that need to be addressed for efficient transport range from short-term to long-term decisions. Notice that two close terms "distribution" and "transport" are commonly used in this domain. In their literature review, [1] deepen the meaning of as follows. Distribution is defined as a planning function implemented at the tactical level defining the quantities to be moved per time period from shippers to customers along a time horizon; this horizon can be one month, a few days or one day. Transport planning is an operational function defining and rationalizing itineraries to ensure the best service quality for the customers.

In this context, the logistics providers have taken an increasingly important place in the organization of the transport and distribution function. These stake holders also called "party logistics" (from 2PL to 5PL) are in charge of executing a more or less significant part of logistics activities. Using their services generally provides means for companies to subcontract storage and transport activities. Additionally some decisions regarding the subcontracting desired for each transport order have to be taken by these logistics providers.

The scope of this paper focus on the first two levels of logistics providers (1PL and 2PL); it could be however extended to take into account the upper levels (3PL up 5PL) of logistics providers. The main objective of this work aims to develop a new approach based on game theory to solve the problem distribution collaboration between carriers. The collaboration is supported by mathematical models implemented with mixed integer linear programming which simulate the planning process.

2. LITERATURE REVIEW

The problem of collaboration in transport and distribution has received a growing interest in research and targets many different domains. For instance, [2] proposed an allocation mechanism to share benefits based on alliance formation among carriers in the maritime field and [3] studied the strategic alliances in freight consolidation. In addition, the collaboration inside supply chain is also a topical subject which has been addressed for many years. The overall objective is to promote win-win opportunities between partners with an appropriate benefit sharing model. Most emphasis has been placed on vertical cooperation between suppliers and customers. Some approaches were developed to manage the collaboration between suppliers and customers such as Vendor Managed Inventory [4] and Collaborative Planning Forecasting and Replenishment [5].

This paper focuses on the horizontal collaboration in transport and distribution, which aims at increasing the profit of transport partners (i.e. carriers). On this topic, a review about horizontal collaboration in transport and logistics was carried out by [6] discussing the main opportunities and impediments in this area. Reference [7] discussed the concepts, the benefits, and some of the environmental challenges of horizontal collaboration in freight transport. According to the studies some authors focused on the profit allocation problem, as [8] [9] [10]. In the field of long distance freight, [11] proposed some formal properties so that coalitions can share gains while avoiding empty kilometers. As far as the methodologies used to support the collaboration are concerned, [12] mentioned that most of the studies use sharing principles based on cooperative game theory.

It appears that little work has been carried out on the tactical collaboration planning for freight distribution which is addressed in this paper. Furthermore there are few studies using the Shapley value for the problem of the planning cooperation between freight carriers. Hence the Shapley value principle is chosen. Most studies using Shapley value in transport and distribution focus on routing problems [13]. These problems are different from the planning problem studied in this paper. The planning model described in this paper is a multi-period model which encompasses a whole planning horizon and which makes it possible among different properties to manage the early and late delivery quantities.

3. PROBLEM DEFINITION

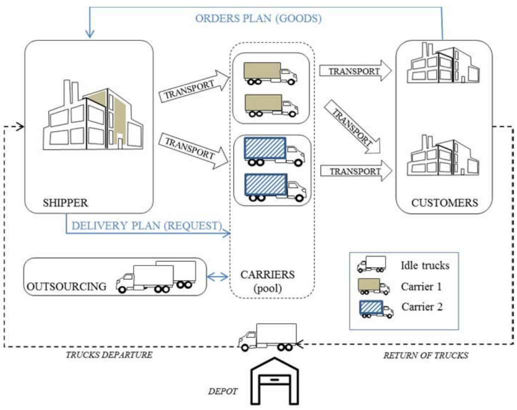

Fig. 1: Problem context

The general context of this study is represented in Fig. 1. It refers to the relationship between a shipper (e.g. manufacturer) and multiple transport operators (so-called carriers). The shipper, which is the client of transport services, has different goods to deliver in order to satisfy the demands of many customers. Each carrier manages a fleet of trucks that have to pick up goods from the shipper and deliver them to the final customers before returning to their initial location. Furthermore, we focus on the carrier's activities by considering that the shipper planning activity is outside the scope of the study. This external partner sends delivery requests to the carriers. When the carriers work alone, they plan their own activities and try to maximize their profit independently from each other's. On the other hand, in the collaborative situation, the global profit of a pool of carriers is optimized while taking into account the whole set of resources of this pool.

This study is based on the following hypothesis:

- Carriers

Each carrier has a limited number of resources (i.e. trucks). Due to this limitation, we set the following assumption: each carrier is allowed to discard part of the shipper demand, without incurring financial penalties for it. This assumption ensures that the carrier is not forced to commit in a non-profitable transaction.

The carrier might use subcontracting when the customer demand requires more than its own current capacity which obviously reduces its profit margin.

In order to optimize its profit, the carrier can propose a pickup and transport plan with slight deviations (late or early delivery) from the request of the shipper. Any variation generates penalties to be paid by the carrier to the shipper affected by this change; those penalties are fixed in a specific agreement between carriers and shipper.

The transport service offered by the carriers is addressed on a general point of view. This service includes all activities related to the freight moves (i.e., dispatching, consolidation, warehousing, and handling). These activities are characterized as a whole, by a round-trip duration defined as the time elapsed between the departure of the truck at the depot and the return time to the depot after having successively visited the shipper and the customer.

- Pool of carriers

Carriers can organize themselves by forming pools in which they group together in order to serve the shipper. The goal of these pools aims to improve the profit of each carrier while obtaining a better distribution of the workload between them. Notice that the size of a pool is from one up to many carriers, the maximum being the total number of carriers.

- Shipper

The planning activity of the shipper is outside the scope of our study but has some impact on the problem studied. The shipper may split the whole demand (deliveries request) into many parts which are assigned to different pools of carriers. Notice that the sum of the demands assigned to all carriers must be equal to the total demand of the shipper. This splitting problem of the workload is not addressed in the paper. It can be based for instance on the operating history of these companies, or based on the relative magnitude of the transport costs of the carriers, or their estimated capacities by the shipper, etc.

In this context, it is proposed that a profit sharing mechanism in order to implement win-win cooperation between the carriers. This requires simulating the planning activities and implementing sharing mechanism. The current study is indeed supported by a numerical simulation, based on a mixed-integer linear programming approach, and an experimental approach.

4. COOPERATIVE FRAMEWORK

The cooperation framework proposed consists of two parts: the transport planning model and the profit sharing mechanism.

4.1. Planning model

Below, we introduce the main modeling hypothesis, the notations, and then the mathematical formulation of our model is described.

Two main assumptions are made:

1) The round-trip time is the duration of moving a truck starting from its depot and returning back to the same depot, after having visited the shipper and a customer. This time includes the transfer lead-time which is the time elapsed from the depot to the shipper, as Fig. 2.

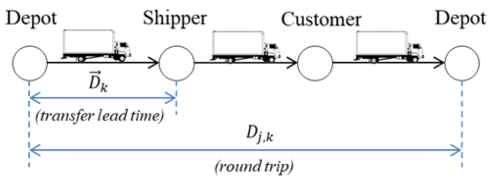

Fig. 2: Transport lead-times

2) The vehicle capacity is defined in terms of weight of the goods.

Let us introduce below the notations used to formulate the mathematical models.

- Set

T	Set of periods
P	Set of goods
J	Sets of customers
N	Sets of carriers

- Indices

t	Index of planning period
p	Index of goods
j	Index of customers
k	Index of carriers

- Parameters

$L_{p,j,k,t}$	Demands of goods p from customer j to carrier k , at time period t
V_p	Scalar representing the unitary weight of goods p
$D_{j,k}$	Round-trip time (i.e. number of periods) needed to serve customer j by carrier k
$\vec{D}_k$	Transfer lead-time (i.e. number of periods) of carrier k between the depot and the shipper
Q_k	Load capacity of trucks owned by carrier k
Q'_k	Load capacity of extra trucks rented by carrier k
R_k	Number of trucks owned by the carrier k
R'_k	Number of extra trucks that can be used by carrier k
M	Large number
a, b	Preferences between the different components of the objective function
$C^e_{p,j,k}$	Unitary penalty cost of goods p demanded by customer j, picked up early by carrier k
$C^l_{p,j,k}$	Unitary penalty cost of goods p demanded by customer j picked up late by carrier k
$C^f_{j,k}$	Fixed transport cost of carrier k using one of its own resources during one time period to serve customer j
$C^v_{p,j,k}$	Variable cost per unit of goods p to be deliver to customer j by the trucks owned by carrier k
$C^{f'}_{j,k}$	Fixed transport cost of carrier k using one of the extra resources to serve customer j
$C^{v'}_{p,j,k}$	Variable cost per unit of goods p to be deliver to customer j by the extra trucks rented by carrier k
$C^t_{p,j,k}$	Transport price per unit of goods p to be deliver to customer j by carrier k
C^a_k	Administrative cost of carrier k

- Variables

$q_{p,j,k,t}$	Quantity of goods p picked up at time period t by own trucks of the carrier k to be delivered from the manufacturer to the customer j
$q'_{p,j,k,t}$	Quantity of goods p picked up at time period t by extra trucks of carrier k to be delivered from the manufacturer to the customer j
$z_{p,j,t}$	Quantity of goods p discarded at time period t which is not be delivered to customer j

$t_{p,j,t}^{e}$	Quantity of goods p requested by customer j and picked up early at time period t
$t_{p,j,t}^{l}$	Quantity of goods p requested by customer j and picked up late at time period t
$m_{j,k,t}$	Number of owned trucks used by carrier k at time period t to serve customer j
$m'_{j,k,t}$	Number of extra trucks used by carrier k at time period t to serve customer j
n_k	Equal to 1 if the carrier is used, 0 otherwise

The objective function (1) is a utility additive function of two terms. The first term "p_T" is the profit of the carriers (1A) to be maximized. The profit is the difference between the revenue (1a) and the total transport costs calculated as the sum of:

1) an administrative cost, which is assigned to any carrier, each time one truck (or more) is required to deliver goods (1b);
2) a fixed cost related to the exploitation of any owned or subcontracted trucks, added with a variable cost that depends on the distance travelled to serve the customers, (1c) and (1d);
3) the cost incurred by the quantities delivered in advance or late (1e).

The second term "s_D", to be minimized, expresses the service quality deviation as the gap between pickup and ordered (i.e. demands) quantities, added with the total quantity discarded by the carrier along the entire time horizon (1B). Indeed, each carrier can refuse any quantity exceeding its capacity to serve his customers. This behavior prevents the carrier from having to respond to all requests with a negative profit induced by the various penalties (i.e. early and late).

- Objective function

$$max\ (a * p_T - b * s_D) \tag{1}$$

with

profit: $p_T = r_T - c_T^0 - (c_T + c'_T) - \bar{c}_T$ (1A)

Revenue: $r_T = \sum_{p\in P}\sum_{j\in J}\sum_{k\in K}\sum_{t\in T}(q_{p,j,k,t} + q'_{p,j,k,t}) * C_{p,j,k}^{t}$ (1a)

Administrative cost: $c_T^0 = \sum_{t\in T} C_k^a * n_k$ (1b)

Transport cost: $c_T = \sum_{j\in J}\sum_{k\in K}\sum_{t\in T} m_{j,k,t} * C_{j,k}^{f} * D_{j,k} + \sum_{p\in P}\sum_{j\in J}\sum_{k\in K}\sum_{t\in T} q_{p,j,k,t} * C_{p,j,k}^{v}$ (1c)

Extra cost: $c'_T = \sum_{j\in J}\sum_{k\in K}\sum_{t\in T} m'_{j,k,t} * C_{j,k}^{f'} + \sum_{p\in P}\sum_{j\in J}\sum_{k\in K}\sum_{t\in T} q'_{p,j,k,t} * C_{p,j,k}^{v'}$ (1d)

Penalty cost: $\bar{c}_T = \sum_{p\in P}\sum_{j\in J}\sum_{k\in K}\sum_{t\in T} t_{p,j,t}^{e} * C_{p,j,k}^{e} + \sum_{p\in P}\sum_{j\in J}\sum_{k\in K}\sum_{t\in T} t_{p,j,t}^{l} * C_{p,j,k}^{l}$ (1e)

Service deviation: $s_D = \sum_{p\in P}\sum_{j\in J}\sum_{t\in T}(t_{p,j,t}^{e} + t_{p,j,t}^{l}) + \sum_{p\in P}\sum_{j\in J}\sum_{t\in T} z_{p,j,t}$ (1B)

- Constraints

$$\sum_{k\in K}(q_{p,j,k,t} + q'_{p,j,k,t}) + z_{p,j,t} - t_{p,j,t}^{e} + t_{p,j,t}^{l} = \sum_{k\in K} L_{p,j,k,t} - t_{p,j,t-1}^{e} + t_{p,j,t-1}^{l} \quad \forall p \in P, \forall j \in J, \forall t \in T \tag{2}$$

$$(q_{p,j,k,t} + q'_{p,j,k,t}) \le L_{p,j,k,t} \quad \forall p \in P, \forall j \in J, \forall k \in K, \forall t \in T \tag{3}$$

$$\sum_{p\in P}\sum_{k\in K} V_p * q_{p,j,k,t} \le \sum_{k\in K} m_{j,k,t} * Q_k \quad \forall j \in J, \forall t \in T \tag{4}$$

$$\sum_{p\in P}\sum_{k\in K} V_p * q'_{p,j,k,t} \le \sum_{k\in K} m'_{j,k,t} * Q'_k \quad \forall j \in J, \forall t \in T \tag{5}$$

$$\sum_{j\in J}\sum_{i=1}^{D_k} m_{j,k,t-i} + \sum_{j\in J}\sum_{i=1}^{D_{j,k}-D_k} m_{j,k,t+i-1} \le R_k \quad \forall k \in K, \forall t \in T \tag{6}$$

$$\sum_{j\in J}\sum_{i=1}^{D_k} m'_{j,k,t-i} + \sum_{j\in J}\sum_{i=1}^{D_{j,k}-D_k} m'_{j,k,t+i-1} \le R'_k \quad \forall k \in K, \forall t \in T \tag{7}$$

$$\text{When } \sum_{j\in J}\sum_{t\in T}(m_{j,k,t} + m'_{j,k,t}) \ge 1, n_k = 1, \text{ otherwise } n_k = 0 \quad \forall k \in K \tag{8}$$

$$q_{p,j,k,t}, q'_{p,j,k,t}, z_{p,j,t}, t_{p,j,t}^{e}, t_{p,j,t}^{l}, m_{j,k,t}, m'_{j,k,t} \ge 0 \quad \forall p \in P, \forall j \in J, \forall k \in K, \forall t \in T \tag{9}$$

This model is generic since it can be used to plan the transport activity of one or more carriers according to the cardinality of set N. It thus makes it possible to plan each pool of carriers regardless of its size.

Equation (2) expresses the gap between the delivery quantities $L_{p,j,k,t}$ requested by the shipper and the total pickup quantities $\sum_{k\in K}(q_{p,j,k,t} + q'_{p,j,k,t})$. Note that in a given time period, the pickup quantities can be more or less than the delivery requests. Note also that some quantities $z_{p,j,t}$ can be discarded when the number of available trucks in insufficient to fulfill the whole demand. Equation (3) ensures that pickup quantities which are delivered to each customer at each time period do not exceed the corresponding demand of goods. Equations (4) - (7) make sure that the limited capacities of the carriers are not exceeded. Equations (4) and (5) respectively define the number of owned and extra vehicles required to serve the pickup quantities (labelled $q_{p,j,k,t}$ and $q'_{p,j,k,t}$) according to the weight of each goods and according to the capacity of each truck. Equations (6) and (7) verify that the required trucks are available along the time periods corresponding to the transfer lead-times and part of the round-trip. Equation (8) use a binary variable (labelled n_k) equals to one if carrier k is used to serve the customers, which results in a fixed administrative cost in the objective function. This equation is then linearized in the model implemented in the solver. Equation (9) ensures that all the variables in the model are not negative.

4.2. Sharing mechanism

In this section, we recall the basic definition of the Shapley value. First, let us define a cooperative game with transferable utility as a pair (N, v), where:

- N is a finite set of players, indexed by i;

- v: $2^N \mapsto R$, is the function assigning a real valued payoff $v(S)$ to each coalition $S \subseteq N$ with $v(\emptyset) = 0$.

- Let $|S|$ be the number of members in coalition S and $N\backslash\{k\}$ be the set N except element k.

Notice that the "grand coalition" is the name given to the coalition made up of all the players of set N.

In a coalition game, an imputation (labelled x) is a vector of players' outcomes. Each element x_i of this vector denotes the share of the grand coalition' s payoff that a player $i \in N$ receives. From a negotiation perspective, the set of imputations can be seen as the set of feasible agreements between the players. In a coalition game (N, v) the pre-imputation set, labelled p, is defined as: $\{x \in R^N | \sum_{k\in N} x_k = v(N)\}$. Based on set p, the imputation set, is defined as: $\{x \in p | \forall k \in N, x_k \geq v(k)\}$.

As regard a cooperative game (N, v) the Shapley value of player k is defined as follows:

$$G_k(N, v) = \frac{1}{N!}\sum_{S\subseteq N\backslash\{k\}}|S|!\,(|N| - |S| - 1)!\,[v(S\cup\{k\}) - v(S)] \qquad (10)$$

Let us also recall the super-additivity property of a game $\mathrm{G} = (N, v)$: for all coalitions $S, M \subset N$, if $S \cap M = \emptyset$ then $v(S \cup M) \geq v(S) + v(M)$. Note that in a super-additive game, the grand coalition gives the highest payoff.

The implementation of the cooperative game proposed in the context of supply chain distribution is based on the following statements: (i) the players of the game are the carriers (i.e. set N) and a coalition of carriers corresponds to a pool containing many carriers; (ii) the evaluation of a coalition is provided by the value of the objective function of the planning model associated to this coalition; (iii) the property of super-additivity has to be verified to decide if the game is cooperative, and therefore the Shapley value is valid. Otherwise, collaboration between carriers cannot be achieved.

5. Conclusion

This paper deals with the collaboration of carriers in charge of planning their activities in order to serve a set of customers, from a shipper. It is proposed a collaborative approach based on the Shapley value in order to fairly share the profit of the grand coalition between all the carriers. It is proposed a mixed-integer linear programming model for the transport planning of all possible coalitions of carriers, which supports the collaboration mechanism in this work.

The numerical cases are not presented in this paper. Hence, the real data will be used to assess the model in the next step.

6. Acknowledgements

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