Allocative Collaborative Profit in Supply Chains

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Abstract

In the age of globalization, great emphasis has been placed on integration throughout the supply chain and consequently, building alliances appears to be a successful way to improve logistics efficiency. In this paper, we consider a distribution system where a set of retailers order a single product from a unique supplier. In such an environment, we identify the cooperative game theory approach as a feasible toolbox to deal with the profit allocation problem. In order to provide a guide for collaboration companies, we design effective and efficient cost allocation methods to ensure the continuity of the collaboration. We propose a method and subsequently this core allocation is compared to well-known methods. We discuss the main advantages and drawbacks of the proposed solution. We observe that our proposed method is computationally efficient and can be implemented to solve real-life sized problems. A numerical example is presented to show the usefulness of this approach.

1 Introduction

In today's marketplace, logistics collaboration is increasingly emerging as a new opportunity for cost saving through internal chain coordination. Logistics collaborations are categorized as vertical, horizontal, or lateral [Simatupang and Sridharan, 2002]. This research paper focuses on one form of coordination in logistics, namely horizontal logistics collaboration, which is considered to be an effective way of reducing logistics costs [Lozano et al., 2013]. Horizontal cooperation is defined as "bundling the transport requirements of companies operating at the same level of the supply chain, which have similar or complementary transportation needs" [Vanovermeire et al., 2014]. [Cruijssen et al., 2007] expressed a more explicit definition as "an active collaboration between two or more firms that operate at the same level of the supply chain and perform a comparable logistics function on the landside".

A major problem of collaboration is to decide how to share costs, profits or resources [Guajardo and Rönnqvist, 2016]. Cooperative game theories are widely used in logistics as a sharing mechanism, this includes the problems of transportation planning [Frisk et al., 2010], traveling salesmen [Sun et al., 2015], vehicle routing [Krajewska et al., 2008], joint distribution [Dai and Chen, 2012] and inventory [Özener et al., 2013].

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In an attempt to find a solution to these problems, game theory is presented in this paper as a feasible tool to deal with profit allocation.

A Joint Replenishment Problem (JRP) is defined as the coordination of multiple items that are jointly ordered and shipped by using a single truck [Goyal, 1974]. Since it became significant in practice, the JRP has grown in importance over the past decade and is of interest to researchers [Arkin et al., 1989, Porras and Dekker, 2008, Qu et al., 2015].

This paper examines the subject of cooperation in a JRP for one-supplier multi-retailer systems under the same cost structure. JRP is a model of the supply chain formed by one supplier and n retailers to deal with optimizing the shipment of goods through shared warehouses. In this situation, the strategic decision is how to allocate the profits (costs) among partners is an important factor in the design of the coalition. The cost allocation problem may be modelled naturally as a cooperative game. Hence, in this research, we used game theory solution concepts to divide the cost among the members of the coalition. More specifically, to examine the question of cost distribution, first we focus on some of the most central solution concepts in cooperative game theory e.g. equal allocation, Shapley value. Furthermore, by integrating cooperative game theory with the joint replenishment problem we propose a new method of cost allocation. The method is based on different distribution keys e.g. volume, capacity. The proposed method is accurate, fair and realistic as compared with conventional methods.

The rest of the paper is organized as follows. Section 2 presents the standard definitions from cooperative game theory, that are applied in the proposed approach for cost allocation in JRP. Section 3 presents the solution methodology. Section 4 illustrates numerical examples and also presents the comparisons between solution methods. Finally, Section 5 concludes this paper and proposes perspectives for further research.

2 Cooperative Game Theory Background

A cooperative game is a pair $G = (N, \nu)$, characterized by a given set of players $N = \{1, 2, ..., |N|\}$ and the characteristic function ν. N is called the *grand coalition.* The *characteristic function* $\nu : 2^N \to \mathbb{R}$ assigns to every nonempty coalition $S \subseteq N$ a value $\nu(S)$, with $\nu(\emptyset) = 0$. The characteristic function may be interpreted as profits or costs. When coalition S cooperates, the total cost $C(S)$ is generated

$$\nu(S) = \sum_{i \in S} C(i) - C(S), \quad \text{for all} \quad S \subseteq N.$$

Some important properties of cooperative games are listed below in order to derive insights concerning the application of solution concepts.

Definition 1. *A coalition S is profitable if and only if $\nu(S) \geq 0$.*

Definition 2. *The game $G = (N, \nu)$ is superadditive if the value ν satisfies the following equation*

$$\nu(S \cup T) \geq \nu(S) + \nu(T) \quad \textit{for all coalitions} \quad S, T \subset N \quad \textit{and} \quad S \cap T = \emptyset. \tag{1}$$

Equation (1) indicates whether two players have an incentive to cooperate and is focused in most applications of cooperative game theory on logistics collaborations e.g. [Krajewska et al., 2008, Frisk et al., 2010, Lozano et al., 2013].

ϕ_i is the cost(profits) allocated to player i, $i \in N$. This vector $\phi = (\phi_1, \phi_2, ..., \phi_{|N|})$ is an element of the $|N|-$ dimensional linear space $\mathbb{R}^N$.. In a *budget balanced* cost allocation, the total cost allocated to the players is equal to the total cost incurred by the grand coalition ($\sum_{i \in \mathbb{N}} \phi_i(\nu) = \nu(N)$). In a *stable* cost allocation, the total cost allocated to a subset of players should be less than or equal to the total cost incurred by that subset $\nu(S)$. The set of cost allocations that are budget balanced and stable is called the *core* of a collaborative game.

Definition 3. *The core of coalitional game $G = (N, \nu)$ is defined as*

$$Core(N, \nu) = \Big\{ x : \sum_{i \in N} \phi_i(\nu) = \nu(N) \wedge \sum_{i \in S} \phi_i(\nu) \geq \nu(S), \; \textit{for all } S \subseteq N \Big\}.$$

The core is the most attractive solution concept in cooperative game theory. It is a set of valid, efficient allocations that cannot be improved upon by a coalition. For a collaborative game, the core may be empty, that is, a balanced budget with stable cost allocations may not be achievable.

The major problem in cooperative game theory is how to allocate the costs of the grand coalition among the players. The allocation vector satisfies a variety of properties, some of them are listed below. Coalitional game $G = (N, \nu)$ is

efficient if $\sum_{i \in N} \phi_i(\nu) = \nu(N)$, this property ensures that the total value of the grand coalition is distributed among the players,

individual rationality if $\forall_{i \in N} \phi_i(\nu) \geq \nu(\{i\})$, it guarantees that each player should at least get what the player would get individually,

collective rationality if $\forall_{i \in S} \phi_i(\nu) \geq \nu(S), \quad \emptyset \subset S \subset N$. If this property is not satisfied, then the players have an incentive to drop out of the grand coalition in order to gain a higher payoff allocation.

The payoffs that secures efficiency and individual rationality are called the *imputation.* No partner would accept an allocation that has no imputation, therefore most of the solution concepts are a set of imputations. Now we present the definition of different fairness properties represented by well-known allocation rules such as equal allocation, the Shapley value [Shapley, 1953], the Nucleolus [Schmeidler, 1969] and the Gately point [Gately, 1974].

2.1 Equal Allocation

Firstly, we introduce the equal allocation rule which awards an equal portion to each player and is defined by the equation

$$\phi_i(\nu) = \frac{\nu(N)}{n}.$$

In general the proportional method is easy to implement due to the fact that it does not take into account the effect of synergies among the players.

2.2 Shapley Value

One of the earliest and most important solution concepts in coalitional game theory is the Shapley value [Shapley, 1953], that is defined based on marginal contribution.

Definition 4. *The marginal contribution of player i to a coalition S is*

$$\nu(S \cup \{i\}) - \nu(S).$$

Definition 5. *The Shapley value is defined by the formula*

$$\phi_i(\nu) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(n - |S| - 1)!}{n!} (\nu(S \cup \{i\}) - \nu(S)), \quad \textit{for all} \quad i \in S.$$

The Shapley value can be explained as the average marginal contribution in which each individual would make it to the grand coalition if it were to form an individual a time. Shapley value allocations may not lie in the core of the game, in cases where the core is non-empty.

2.3 Nucleolus

In addition to the Shapley value another solution concept that is studied in cooperative game theory is the Nucleolus [Schmeidler, 1969]. When we compute the Nucleolus of a game, we lexicographically maximize the minimal gain, the difference between the stand alone cost of a subset and the total cost allocated to that subset, over all the subsets of the collaboration.

Consider $x \in G(N, \nu)$. For each such x and for each $S \in 2^N \setminus \{N, \emptyset\}$, define the excess of coalition S at x as

$$e_S(x) = x(S) - \nu(S),$$

that measures the "degree of happiness" of each coalition S. Define the vector $e(x) = (e(x))_{S \in s^N \setminus \{N, \emptyset\}}$. This is the vector of all *excesses* of the different coalitions at x.

Definition 6. *Let $r(x)$ be a vector arranged in order of decreasing magnitude. Then, for any pair of payoff vectors x and y, for the first entry z in which they differ, x is smaller than y in the lexicographical order. Let the lexicographical order be denoted by $\succ_{lxm}$.*

Definition 7. *The Nucleolus of the game (N, ν) is*

$$nc(N, \nu) = \{x \in X(N, \nu) : \textit{there does not exists } y \in X(N, \nu)), \quad e(y) \succ_{lxm} e(x)\}.$$

The Nucleolus is the imputation that maximizes the minimal excess and determines such an allocation that the smallest satisfaction is maximized. And hence, it is ensured that the least satisfied coalition is as satisfied as possible.

2.4 Gately Point

In addition to the Shapley value and the Nucleolus, an interesting solution concept for coalitional games is the Gately point [Gately, 1974].

Definition 8. *The Gately point is defined by the formula*

$$G_i(\nu) = \frac{\nu(N) - \nu(N \setminus \{i\})}{\sum_{j \in N}(\nu(N) - \nu(N \setminus \{j\}))}\nu(N).$$

This concept attempts to ensure that the most valuable coalition members retain the most importance.

3 Model Description

Let us consider the example of a group of retailers who decide to cooperate by ordering jointly via a single large order. The mathematical model is developed based on the following assumptions

- the group of retailers can only make orders for full truckload delivery,
- the demand of each retailer is deterministic, and there is no shortage,
- the transportation cost is not relevant to the transportation quantity.

The notions and parameters of the model are summarized in Table 1.

Table 1: Notion

$N = \{1, 2, ...n\}$	set of retailers	Cap_i	vehicle capacity
$Dist_i$	travel distance	F_i	ordering frequency of retailer i
β_i	cost per kilometer	$CO(S)$	ordering cost of coalition S
H_i	holding cost	$CH(S)$	holding cost of coalition S
D_i	demand of retailer i	$CT(S)$	travel cost of coalition S
A	fixed ordering cost	$C(S)$	total cost of coalition S
V_i	volume of i retailer' product	$CS(S)$	cost saving of coalition S
Q_i	order size of i retailer		

In the optimal replenishment strategy under full truckload (FTL) shipments ($V_i \cdot Q_i = CAP_i$), the carriers have a similar cost structure. Various cost functions in FTL have been proposed in the literature (e.g. [Qu et al., 2015]). In [El Omri, 2009], the proposed cost function is based on the combination of two different types of costs: ordering costs $CO(S)$ and holding costs $CH(S)$ as follows

$$CO(S) = A \cdot \sum_{i \in S} F_i, \quad CH(S) = \frac{\sum_{i \in S} H_i}{\sum_{i \in S} F_i} \quad \emptyset \subset S \subseteq N,\ i \in \{1, 2, ..., n\},$$

where

$$F_S = \sum_{i \in S} \frac{D_i \cdot V_i}{Cap_i} = \sum_{i \in S} F_i, \quad \emptyset \subset S \subseteq N,\ i \in \{1, 2, ..., n\}.$$

However, from the retailers point of view, the function used in the above scheme does not provide player satisfaction in terms of all of the costs incurred. As a result a more advanced cost function is needed in order to evaluate the impact of transportation costs, defined by (2), with the collaboration mechanism

$$CT(S) = \sum_{i\in S} \beta_i Dist_i, \quad \emptyset \subset S \subseteq N,\ i \in \{1,2,...,n\}. \tag{2}$$

Consequently, the total average cost of the coalition $\emptyset \subset S \subseteq N$ is the sum of the ordering cost, holding cost and transportation cost, as follows

$$C(S) = \underbrace{A \cdot \sum_{i\in S} F_i}_{\text{ordering cost}} + \underbrace{\frac{\sum_{i\in S} H_i}{\sum_{i\in S} F_i}}_{\text{holding cost}} + \underbrace{\sum_{i\in S} \beta_i Dist_i}_{\text{transportation cost}} = CO(S) + CH(S) + CT(S), \quad i \in \{1,2,...,n\}. \tag{3}$$

Lemma 1. *The cost savings function $C(S)$ is a profitable supperadditive function.*

Proof. The cost saving function is profitable if for every $S \subseteq N$ we have $C(S) \leq \sum_{i\in S} C(i)$.
Let $S \neq \emptyset$ then from (3) we have the following

$$\begin{aligned} C(S) &= A\sum_{i\in S} F_i + \frac{\sum_{i\in S} H_i}{\sum_{i\in S} F_i} + \sum_{i\in S} \beta_i Dist_i \\ &\leq A\sum_{i\in S} F_i + \sum_{i\in S} \frac{H_i}{F_i} + \sum_{i\in S} \beta_i Dist_i \\ &= \sum_{i\in S} C(i). \end{aligned}$$

Let S and T be two disjointed and non-empty coalitions, then

$$\begin{aligned} C(S) + C(T) &= A(\sum_{i\in S} F_i + \sum_{i\in T} F_i) + \frac{\sum_{i\in S} H_i}{\sum_{i\in S} F_i} + \frac{\sum_{i\in T} H_i}{\sum_{i\in T} F_i} + \sum_{i\in S} \beta_i Dist_i + \sum_{i\in T} \beta_i Dist_i \\ &\geq A(\sum_{i\in S} F_i + \sum_{i\in T} F_i) + \frac{\sum_{i\in S} H_i + \sum_{i\in T} H_i}{\sum_{i\in S} F_i + \sum_{i\in T} F_i} + \sum_{i\in S} \beta_i Dist_i + \sum_{i\in T} \beta_i Dist_i \\ &= A\sum_{i\in S\cup T} F_i + \frac{\sum_{i\in S\cup T} H_i}{\sum_{i\in S\cup T} F_i} + \sum_{i\in S\cup T} \beta_i Dist_i \\ &= C(S \cup T). \end{aligned}$$

□

Corollary 1. *Since $C(S) \leq \sum_{i\in S} C(i)$ then $\nu(S) \geq 0$. This implies that every coalition S is profitable.*

The idea is defined, based on the cost defined by (3), a profit allocation, namely the Ordering Holding Transportation solution (OHT-solution). The total holding and transportation cost is reduced for each retailer i when they order jointly.

Definition 9. *The OHT-solution $\phi_i(\nu)$, that assigns to each retailer i in coalition S, $\emptyset \subset S \subseteq N$, their cost savings allocation is defined by the formula*

$$\phi_i(\nu) = \beta_i(1-\gamma)Dist_i + \frac{H_i}{F_i} - \frac{H_i}{\sum_{j\in S} F_j}, \quad i,j \in \{1,2,...,n\},\ \gamma \in (0,1).$$

Theorem 1. *The OHT-solution $\phi_i(\nu)$ lies in the core, $\phi_i(\nu) \in Core(N, \nu)$.*

Proof. For every $\phi_i(\nu) = \beta_i(1-\gamma)Dist_i + \frac{H_i}{F_i} - \frac{H_i}{\sum_{j\in N} F_j}$ and $i \in S$ we have

Efficiency

$$\begin{aligned} \sum_{i\in N} \phi_i(\nu) &= \sum_{i\in N}(\beta_i(1-\gamma)Dist_i + \frac{H_i}{F_i} - \frac{H_i}{\sum_{j\in S} F_j}) \\ &= \sum_{i\in N}(\beta_i(1-\gamma)Dist_i + \frac{H_i}{F_i} - \frac{H_i}{F_N}) \\ &= (1-\gamma)\sum_{i\in N} \beta_i Dist_i + \sum_{i\in N} \frac{H_i}{F_i} - \frac{\sum_{i\in N} H_i}{F_N} \\ &= \nu(N), \quad \text{for all } i \in N. \end{aligned}$$

Individual rationality

$$\phi_i(\nu) = \beta_i(1-\gamma)Dist_i + \frac{H_i}{F_i} - \frac{H_i}{F_N} \geq 0 = \nu(i), \quad \text{for all } i \in N,\ F_N \geq F_i,\ 0 < \gamma < 1.$$

Collective rationality

$$\begin{aligned}
\sum_{i\in S}\phi_i(\nu) &= \textstyle\sum_{i\in S}(\beta_i(1-\gamma)Dist_i + \frac{H_i}{F_i} - \frac{H_i}{\sum_{j\in S}F_j}) \\
&= \textstyle\sum_{i\in S}(\beta_i(1-\gamma)Dist_i + \frac{H_i}{F_i} - \frac{H_i}{F_N}) \\
&= \textstyle(1-\gamma)\sum_{i\in S}\beta_i Dist_i + \sum_{i\in S}\frac{H_i}{F_i} - \frac{\sum_{i\in S}H_i}{F_N} \\
&\geq \textstyle(1-\gamma)\sum_{i\in S}\beta_i Dist_i + \sum_{i\in S}\frac{H_i}{F_i} - \frac{\sum_{i\in S}H_i}{F_S} = \nu(S), \quad \text{for all } i \in S.
\end{aligned}$$

□

4 Simulation Result and Analysis

In this section, an illustrative example of four retailers (label A, B, C, D) supplied by the same manufacturer is presented and analyzed. The travel distance, holding and ordering cost, product volume, vehicle capacity, demand of each retailer, and ordering frequency are shown in Table 2. Notice that retailer D offers the lowest total cost. In addition, it has the lowest transportation cost. However, retailer D also offers one of the highest ordering costs. This prevents the existence of a dominant position in the process of grand coalition formation. The total cost for each possible coalition S and their savings ratio are shown in Table 3. The grand coalition $\{A, B, C, D\}$ is stable, which means that no sub-coalition has an incentive to leave the grand coalition. In addition, for the CS function the monotonicity and superadditivity properties hold.

Table 2: Retailers' costs

Retailer	$Dist_i$	H_i	A	V_i	Cap_i	D_i	F_i	$CO(S)$	$CH(S)$	$CT(S)$	$C(S)$
$\{A\}$	150	300	20	1	50	600	12	240	25	600	865
$\{B\}$	170	100	20	1	50	100	2	40	50	680	770
$\{C\}$	150	100	20	1	50	50	1	20	100	600	720
$\{D\}$	130	200	20	1	50	150	5	100	45	500	645

Table 3: Coalitions costs and savings

Coalition	$C(S)$	$CS(S)$	Contribution to the grand coalition
$\{A\}$	865.0	0.0	896.3
$\{B\}$	770.0	0.0	2 318.4
$\{C\}$	720.0	0.0	2 433.3
$\{D\}$	645.0	0.0	1 893.2
$\{A, B\}$	1 204.6	430.4	
$\{A, C\}$	1 130.8	454.2	
$\{A, D\}$	1 153.4	356.6	
$\{B, C\}$	1 022.7	467.3	
$\{B, D\}$	1 022.9	393.1	
$\{C, D\}$	954.0	411.0	
$\{A, B, C\}$	1 649.3	705.7	
$\{A, B, D\}$	1 671.6	608.4	
$\{A, C, D\}$	1 597.3	632.7	
$\{B, C, D\}$	1 470.0	665.0	
$\{A, B, C, D\}$	2 115.0	885.0	

In section 3 a new method of allocating of profits was introduced, the so-called ordering-holding-transportation solution (OHT-solution). This solution belongs to the core of the game, which implies that the solution is stable in the sense that no player is motivated to break off and form their own coalition. Table 4 indicates the comparison of costs allocated to each of the retailers A, B, C, D based on each method. The results in this study were obtained from equal allocation, Shapley value, Nucleolus, Gately point and OHT-solution. For each allocation concept, the Cost Saving is calculated according to the definition and formula presented in section 2. Net Cost equals the Stand-alone Cost minus Cost Savings. The total cost saving is 885. The Savings Ratio equals the Cost Savings divided by the Net Cost.

Table 4: Results for test instances

Carriers in coalitions	A	B	C	D
Stand-alone cost	865	770	720	645
	Equal allocation			
Cost saving	221.3	221.3	221.3	221.3
Net cost	643.8	548.8	498.8	423.8
Savings ratio	25.6 %	28.7 %	30.7 %	34.3 %
	Shapley value			
Cost saving	214.8	233.7	248.9	187.7
Net cost	650.2	536.3	471.1	457.3
Savings ratio	24.8 %	30.3 %	34.6 %	29.1 %
	Nucleolus			
Cost saving	209.2	241.5	265.8	168.5
Net cost	655.8	528.5	454.2	476.5
Savings ratio	24.2 %	31.4 %	36.9 %	26.1 %
	Gately point			
Cost saving	209.8	240.6	263.7	171.0
Net cost	655.2	529.4	456.3	474.0
Savings ratio	24.2 %	31.2 %	36.6 %	26.5 %
	OHT-solution			
Cost saving	190.0	249.0	275.0	171.0
Net cost	675.0	521.0	445.0	474.0
Savings ratio	22.0 %	32.3 %	38.2 %	26.5 %

These results show clearly that it is worthwhile cooperating in a single-supplier multi-retailer problem with full truckload shipments in order to save costs. The cost savings range from 22% to 38.2%. We can see that individual C gets the maximum profit according to the OHT-solution while retailer C has also makes the largest contribution to the grand coalition (equal 2 433.32). Hence, it is easy to conclude that retailer C should prefer the OHT-solution. In contrast, an equal allocation would probably cause the coalition to be disbanded since retailer C gains smaller savings than retailer D but it still contributes to the grand coalition. The Shapley value and Nucleolus, which is less practical and may be more costly, may be rejected by any of them. However, it must be stressed that all of the concepts (except for equal allocation) are fair in the sense that the retailers who contribute more are paid more.

5 Conclusion and Further Research

This paper examines a set of cost allocation methods which depends on the situation whereby there are multiple decision makers who obtain benefits by full truckload shipments cooperation. Motivated by this problem, the primary focus of the paper is to make use of well-known game theoretical concepts and introduce new allocation rules that arise from the practical situation (OHT - solution). In this paper the equal allocation, Shapley value, Nucleolus, and Gately point have been used to investigate their effectiveness in a fair cost sharing between companies. We find that under the methods proposed, companies have an incentive to collaborate since this results in reduced costs. In addition, we also explored the issues concerning the detailed comparison of the proposed allocation methods. The results indicated that the methods proposed can lead to a fair cost allocation, since a method such as OHT-solution may establish an adequate incentive for collaboration. Further, the OHT-solution is a suitable allocation since it is designed especially for this kind of cooperation.

Further research may take a number of different directions. First of all, it is worth to discuss the applicability of the proposed approach to dynamic distribution systems. Second direction is to consider multiple suppliers. Another possible direction is to extend the model by considering multiple objectives, such as the supply chain risk. Finally, an assumption of the approach discussed in the paper is that all the trips are full-truck-load. The long-term goal is to elaborate the paper to consider less-than-truck load scenarios. However, this approach may increase the model's computational complexity.

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