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Analysis of collaborative savings and cost allocation techniques for the cooperative carrier facility location problem

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Abstract

Transport companies may cooperate to increase their efficiency levels by e.g. the exchange of orders or vehicle capacity. In this paper a new approach to horizontal carrier collaboration is presented: the sharing of distribution centres (DCs) with partnering organisations. This problem can be classified as a cooperative facility location problem and formulated as an innovative mixed integer linear program. To ensure cooperation sustainability, collaborative costs need to be allocated fairly to the different participants. To analyse the benefits of cooperative facility location and the effects of different cost allocation techniques, numerical experiments based on experimental design are carried out on a U.K. case study. Sharing DCs may lead to significant cost savings up to 21.6%. In contrast to the case of sharing orders or vehicles, there are diseconomies of scale in terms of the number of partners and more collaborative benefit can be expected when partners are unequal in size. Moreover, results indicate that horizontal collaboration at the level of DCs works well with a limited number of partners and can be based on intuitively appealing cost sharing techniques, which may reduce alliance complexity and enforce the strength of mutual partner relationships.

Keywords: Horizontal cooperation, Facility location, Logistics, Cooperative game theory, Cost allocation

Introduction

The purpose of this article is to extend the current literature on horizontal collaboration between carriers to the case where these organisations would share their distribution centres (DCs). An integer linear programming model is presented and used in an experimental design in a U.K. case context to investigate the benefits of cooperation between two or three carrier organisations. Several techniques from the literature to allocate cost savings among the participants are compared.

Horizontal collaboration between logistics service providers is an important research area, since severe competition in global markets, rising costs, a growing body of transport legislation, and increased customer expectations have caused profit margins of carriers to shrink (Cruijssen et al, 2007b). Traditionally, transport organisations rely on their internal potential to reduce costs. Most logistics service providers, however, have exhausted the opportunity to improve efficiency through process optimisation and the application of new technologies. In order to cope with the ever increasing pressure to operate more efficiently, the firms may find it in their interest to adopt a collaborative focus, thereby opening up cost saving opportunities that are impossible to achieve with an internal company focus only (Ergun et al, 2007; Wang and Kopfer, 2011).

Horizontal logistics cooperation may be defined as collaboration between two or more firms that are active at the same level of the supply chain and perform comparable logistics functions (Cruijssen et al, 2007c). Through partnering with fellow transport organisations, carriers may extend their resource portfolio, reinforce their market position, and create a more efficient transport planning function (Krajewska and Kopfer, 2006a). Analysis of existing scientific research on horizontal carrier collaboration reveals that the majority of logistics cooperation literature may be divided into two main research streams (Verdonck et al, 2013). Most of the articles concerning horizontal carrier cooperation are devoted to carrier alliances in which customer requests or orders are exchanged between the participating organisations through various techniques. The main purpose of this request re-allocation is to achieve a better match between requested and available transportation resources (Bloos and Kopfer, 2011). Through order sharing, carriers may improve their efficiency and profitability because of an increase in capacity utilisation, improved asset repositioning capabilities, and a reduction in total transport costs due to improved transport planning (Kopfer and Pankratz, 1999; Dai and Chen, 2011). Instead of sharing customer requests, carriers may also cooperate horizontally through the sharing of vehicle capacity. Since owning a vehicle involves a considerable capital investment, and low capacity utilisation reduces a company's efficiency, logistics service providers may cooperate horizontally to share capacity and its associated costs (Agarwal and Ergun, 2010). Capacity sharing provides a suitable alternative for order sharing, especially in environments where private order information cannot be communicated between alliance partners.

Existing studies on horizontal carrier cooperation all focus on collaboration opportunities within a transport context. In line with the broad definition of logistics, this paper presents a new approach to carrier cooperation: the sharing of warehouses or distribution centres (DCs) with collaborating partners. By jointly and optimally deciding on two types of decisions, namely first which DCs to open, and second how to allocate the quantity of product flows to each open DC, partnering companies aim to minimise their total logistics cost. This total cost consists of fixed costs of keeping DCs open, and all costs of primary transport (between company depots and DCs) and secondary transport (between DCs and customer zones). In addition, variable costs incurred in each DC for each type of product can be added to the primary transport costs, and variable costs incurred in each customer zone upon delivery of each type of product can be added to the secondary transport costs. As this paper demonstrates, sharing DCs with partner organisations can lead to significant cost reductions.

The cost minimisation problem described above can be classified as a facility location problem under cooperation (Goemans and Skutella, 2004). Until now, the cooperative facility location problem has been studied exclusively in a customer-centred context. The participants in the grand coalition being the individual customers, this leads to typically very large grand coalitions. The novel application of the cooperative facility location problem to the case of horizontal carrier collaboration requires a different focus, since the participants of the grand coalition are now the carriers and hence this number tends to be very small in comparison. This enables us, however, to focus more on the problem of partner selection. To this end, this paper presents an innovative mathematical model that allows such investigations to be carried out using one single mixed integer linear program (MILP). As our numerical experiments demonstrate, partner selection is an important aspect as it determines not only whether potential problems of coalition instability may occur, but also influences the cost savings achievable.

As in any collaboration, dividing the coalition gains in a fair manner between the participants constitutes a key issue. Any allocation mechanism should induce partners to behave according to the collaborative goal, and should strive to improve cooperation stability. In current customer-centred facility location literature, the allocation problem is solved exclusively by applying game theory (Tamir, 1993; Chardaire, 1998; Goemans and Skutella, 2004; Mallozzi, 2011). As these game theoretic mechanisms, like the Shapley value, may raise questions from transportation companies about mathematical complexity, applicability, fairness transparency, and stability, this paper applies two additional cost allocation techniques to the cooperative carrier location problem. Our numerical experiments indicate modest differences between the allocation techniques, suggesting the support of the practical recommendation that firms may choose the technique which best supports operational implementation and intuition.

The main scientific contributions of this paper can be summarised as follows. First, the literature on horizontal carrier collaboration is extended to the case of sharing DCs. Second, the cooperative facility location model is reformulated to make it fit this context and such that it can be easily applied to investigate partner selection. Partner selection is a feature that is absent from the current customer-centred cooperative facility location literature, but an important aspect in horizontal logistics collaboration, see also Vanovermeire et al (2013a). Third, numerical experiments are conducted based on an experimental design applied to a U.K. case study to analyse the relative benefits of different coalitions and different cost allocation mechanisms. We compare our findings with general recommendations from the literature on horizontal collaboration of transport organisations. This leads to a number of new insights, including that in the context of DC sharing, economies of scale in terms of number of partners does not necessarily result in a better performance for participants, and that operational fit of partners may in fact mean inequality of organisations rather than them being as equal as possible.

The remainder of this paper is organised as follows. The sections ‘The cooperative facility location problem’ and ‘Collaborative cost allocation’ summarise the current research field of cooperative facility location and cost allocation respectively. Moreover, differences between existing research work and models and applications presented in this paper are clarified. In the next two sections mathematical models are presented for the facility location problem under carrier cooperation and the applied cost allocation mechanisms. Extensive numerical experiments are carried out on a U.K. case study in the section ‘Experimental design and numerical results’. The goal of the experimental design is to investigate a number of hypothetical relations introduced in current collaboration literature between cooperation characteristics, collaborative performance, and cost allocation results using a well-known statistical research method. Finally, conclusions and directions for future research are formulated.

The cooperative facility location problem

In general, the facility location problem may be described as follows. Given a set of possible locations for facilities and a set of customer locations to serve, the goal is to locate facilities in such a way that the total cost for keeping these facilities operational while satisfying customer demand is minimised. The facility location problem may be classified into different categories, depending on the assumed restrictions. As such, a distinction can be made between the uncapacitated and the capacitated version of the problem, based on the existing capacity limits of each facility. In addition, the single-source and multi-source problem can be discerned, depending on the number of facilities that are allowed to serve each customer (Holmberg et al, 1999). Reviews of the facility location problem can be found in Klose and Drexl (2005) and ReVelle et al (2008).

Analysing current facility location literature, the horizontal cooperation approach of carriers sharing distribution centres can be classified as a facility location problem under cooperation. Until now, the cooperative facility location problem has been studied exclusively in a customer-centred context. The goal of the cost allocation problem is to allocate the optimised location cost to the customers such that no coalition of customers has the incentive to build their own facilities or to ask a competitor to service them. It is also well-known from this literature that, even though these games are typically superadditive, the core of the game may well be empty and that there could thus be problems related to achieving stable outcomes for the grand coalition. Tamir (1993) studies the allocation of costs to the customers in a general facility location framework applying game theory. Chardaire (1998) investigates optimised facility location and fair sharing of total costs to the end-users of telecommunication networks. Goemans and Skutella (2004) consider the cost minimising location of public facilities (e.g. libraries, fire stations) or private facilities (e.g. distribution centres, supermarkets) in order to provide a certain level of service to customers. Mallozzi (2011) studies a single-facility location problem for which the location cost depends on the region where the new facility is located.

The existing research work on the cooperative facility location problem focuses on a customer-centred approach where out of a given set of potential locations an optimal set has to be selected for building facilities and the total minimum location costs so achieved are then to be allocated to customers in a fair manner using game theory concepts. In our context of horizontal collaboration, not only will the set of customers but also the set of potential locations of DCs vary with the selection of partners, and the cost allocation has to occur not between customers but the carriers in the coalition. The issues of partner complementarity and partner selection are now integral parts of the decision process. Following these observations, a contribution of our work is thus the novel applicability of the cooperative facility location model in a carrier collaboration environment, requiring a different focus.

Collaborative cost allocation

As the goal of a horizontal logistics cooperation is to increase the participants' logistics efficiency and since collaboration often results in additional profits or cost savings, a great deal of scientific literature on collaborative logistics devotes its research attention to the identification of efficient allocation schemes (Krajewska and Kopfer, 2006b). Dividing the coalition costs or gains in a fair manner constitutes a key issue, since the proposed allocation mechanism should induce partners to behave according to the collaborative goal and may improve cooperation stability.

Table 1 Overview of allocation mechanisms

Allocation mechanism	**Reference**	**Area of application**
Proportional	Frisk et al (2010)	Collaborative forest transport
	Liu et al (2010)	Horizontal carrier cooperation
Cooperative game theory	Shapley (1953)	General n-person games
	Schmeidler (1969)	Characteristic function game
	Krajewska and Kopfer (2006a)	Horizontal carrier cooperation
	Krajewska et al (2008)	Horizontal carrier cooperation
	Agarwal et al (2009)	Carrier alliances in liner shipping
	Agarwal and Ergun (2010)	Carrier alliances in liner shipping
	Frisk et al (2010)	Collaborative forest transport
	Liu et al (2010)	Horizontal carrier cooperation
	Houghtalen et al (2011)	Horizontal carrier cooperation
	Dai and Chen (2012)	Horizontal carrier cooperation
	Lozano et al (2013)	Horizontal shipper cooperation
Additional cooperation properties	Tijs and Driessen (1986)	General cost games
	Özener and Ergun (2008)	Horizontal shipper cooperation
	Frisk et al (2010)	Collaborative forest transport
	Liu et al (2010)	Horizontal carrier cooperation
	Audy et al (2011)	Cooperation in furniture industry

A review of current logistics cooperation literature on the allocation topic reveals that various techniques may be distinguished to share collaborative profits or costs. Next, we provide an overview covering proportional sharing mechanisms ('Proportional allocation mechanisms'), allocation mechanisms using game theory concepts ('Allocation mechanisms based on cooperative game theory'), and allocation techniques designed to cope with additional cooperation properties ('Allocation mechanisms with additional desirable properties'). In Table 1, relevant references related to allocation mechanisms are summarised together with the cooperation contexts in which they have been applied.

Proportional allocation mechanisms

In practice, the most commonly used profit or cost division mechanism is the proportional allocation method (Liu et al, 2010). In this case, the collaborative profit is allocated to the cooperating organisations equally, on the basis of their individual cost level (stand-alone cost) or the volume they have to transport as a consequence of their engagement in the cooperation. The reason for the widespread use of the proportional allocation technique lies in the fact that it is easy to understand, compute and implement. However, it does not guarantee long term collaboration stability since it is possible that an individual partner leaves the partnership considering the fact that he may gain more when operating on an individual basis (Liu et al, 2010). Even if stable, it may still be considered to produce unfair divisions of the coalitional benefits. As such, it is not further considered in this paper.

Allocation mechanisms based on cooperative game theory

A horizontal logistics cooperation clearly matches the structure of a cooperative game. Collaborating partners exchange orders or resources and receive or make payments in return. This cooperation process results in an allocation of benefits or costs to each participant which may be considered equivalent to the outcome of a cooperative game (Houghtalen et al, 2011). Moreover, Cruijssen et al (2007b) state that the advantages of applying game theory in a logistics cooperation context are that these allocation methods account for the different contributions of the alliance participants and that they define allocations that distribute the collaborative benefits based on fairness properties.

The workings of a horizontal logistics cooperation may be formally described in terms of game theory concepts. The grand coalition N coincides with all participating companies i in the cooperation, while a coalition S denotes a subset of collaborators. When a coalition S collaborates, they realise a certain amount of collaborative costs which can be captured using the function $c(S)$. As such, the benefits or cost savings generated by a coalition S, $\forall S \subseteq N$, denoted by the characteristic function $v(S)$, are equivalently calculated as $\sum_{i \in S} c(i) - c(S)$. The cost amount allocated to partner i, assuming all players cooperate, is defined by y_i $(i \epsilon N)$.

A relevant concept in the context of logistics cooperation is the notion of the core (Shapley, 1952; Gillies, 1959). The core of a game consists of all profit allocations that are budget balanced ($\sum_{i \in N} y_i = c(N)$) and guarantee that no single participant or coalition of participants benefits from leaving the cooperation ($\sum_{i \in S} y_i \leq c(S), \forall S \subseteq N$). A drawback of this solution concept is the fact that the core of a cooperative game may be empty. To compensate for this shortcoming, several extensions have been developed which relax inequalities that define the core. Examples are the least core (Drechsel and Kimms, 2010) and the minmax core (Drechsel and Kimms, 2011). In relation to this core, the excess can be computed for each coalition S. This excess constitutes the difference between the total cost of a coalition and the sum of the costs allocated to its participants: $-c(S) + \sum_{i \in S} y_i, \forall S \subseteq N$. For a given cost allocation, any strictly positive value may be seen as a measure of how far the allocation lies from the core (Frisk et al, 2010; Liu et al, 2010).

A well-known allocation method based on the foundations of game theory is the Shapley value (Shapley, 1953). This value allocates to each participant the weighted average of his contributions to all (sub)coalitions, assuming the grand coalition is formed one company at a time. A detailed theoretical description and a numerical application of the classic Shapley value to the cooperative facility location problem can be found in the sections ‘Cost allocation mechanisms: Description, calculation, and properties‘ and ’Experimental design and numerical results’, respectively. Another basic allocation mechanism supported by game theory is the nucleolus. This profit or cost sharing procedure, developed by Schmeidler (1969), has the distinct property of minimising the maximal excess, as defined above. The nucleolus is unique and if the core is not empty, it lies in the core and provides a stable allocation. However, this allocation mechanism does not consider the individual participants' contributions to the coalition (Frisk et al, 2010; Liu et al, 2010). In comparison to the Shapley value, the calculation of the nucleolus is rather intricate as it involves solving a series of linear programs. Lozano et al (2013) compare the performance of the Shapley value, the nucleolus, and core approximations with respect to the allocation of savings in the context of horizontal shipper collaboration.

Krajewska and Kopfer (2006a) propose a more complex profit sharing model based on game theory in combination with auction mechanisms. First, collaborative profits are maximised using combinatorial auction techniques to exchange customer orders optimally. Then, transfer prices are used to divide collaborative savings among partnering carriers such that the current financial situation of each partner is at least maintained (individual rationality). In addition, residual profits created during the collaboration process are shared between the cooperating partners on the basis of collaboration advantage-indexes. These indexes account for the individual contribution of the different participants to the cooperation.

In line with the previous article, Dai and Chen (2012) develop an allocation mechanism accounting for the contribution of each individual carrier to the coalition. The goal is to find profit allocations that minimise the difference between contribution-based allocation ratios of any two carriers. Moreover, the authors ensure allocation stability through the application of core characteristics.

Finally, in Agarwal et al (2009) and Agarwal and Ergun (2010) the division of collaborative profit is considered in the context of capacity sharing in the liner shipping industry. Both articles propose a similar procedure, fitting in the game theory framework and applying inverse optimisation techniques, to determine capacity exchange costs or side payments. As in a cooperative game, these payments have the purpose of motivating the individual cooperating partners to act in the best interest of the overall cooperation project and to pursue the solution suggested by the collaborative optimisation model.

Allocation mechanisms with additional desirable properties

Basic game theoretic allocation mechanisms may raise questions among logistics service providers concerning mathematical complexity, applicability, fairness transparency, and stability in practice. As such, several authors have developed distinct, more intuitively clear allocation mechanisms which account for certain specific cooperation characteristics, some of them partly based on game theory ideas.

Tijs and Driessen (1986) point out that a suitable allocation mechanism may be based on the division of the total collaborative costs in separable and non-separable costs. In the first step of the allocation procedure, each participant is allocated its separable or marginal cost, which reflects the increase in total collaborative costs when this carrier joins the collaboration. Secondly, the remainder of the total costs, labelled non-separable costs, are distributed among the cooperating companies according to specific weights. In this way, the allocation mechanism accounts for the different impacts collaborating companies may have on the total logistics cost level. The authors describe three versions of non-separable cost allocation methods: the Equal Charge Method (ECM), the Alternative Cost Avoided Method (ACAM), and the Cost Gap Method (CGM) which correspond to differences in chosen weights and allocation characteristics. A detailed theoretical description and a numerical application of the ACAM to the cooperative facility location problem can be found, respectively, in the sections 'Cost allocation mechanisms: Description, calculation, and properties' and 'Experimental design and numerical results'.

In the early phases of a growing horizontal cooperation, it may be helpful for communication and negotiation purposes to have an initial allocation where the relative benefits of the participating organisations are as similar as possible. For this purpose, Frisk et al (2010) develop the Equal Profit Method (EPM). This profit sharing technique has the goal of finding a stable allocation that minimises the largest relative difference in cost savings between any pair of cooperating partners. Liu et al (2010) develop a similar procedure, labelled Weighted Relative Savings Model (WRSM), which additionally takes the different contribution levels of the cooperators into account. A detailed theoretical description and a numerical application of the EPM to the cooperative facility location problem can be found in the sections 'Cost allocation mechanisms: Description, calculation, and properties' and 'Experimental design and numerical results' respectively. Audy et al (2011) develop a modified version of both the EPM and the ACAM fitting various collaboration scenarios in the Canadian furniture shipping industry.

In some situations it might be desirable to relax the stability or efficiency properties of a cost or profit sharing technique in order to create an allocation mechanism with other advantageous characteristics. In this context, Özener and Ergun (2008) develop allocation mechanisms based on the lane covering problem of a horizontal shipper collaboration satisfying three additional characteristics. First, cross-monotonicity ensures that when a new transport company enters the horizontal cooperation, the allocated benefit of the existing partners does not decrease. Second, the minimum liability concept guarantees that every cooperation participant pays at least its individual cost. In this way, situations where shippers have to cover the expenses of partners and others become free riders with zero allocated costs are avoided. Finally, mechanisms are created which generate positive benefit cost allocations. Every participating company expects to gain when entering a horizontal cooperation.

So it may be desirable to identify cost allocations ensuring that each partner is charged less than his individual cost. As Özener and Ergun (2008) prove that it is not possible to find core allocations satisfying these additional constraints, they relax efficiency and stability properties respectively.

Allocation mechanisms in perspective

The overview provided in the previous subsections demonstrates that a wide range of possible allocation mechanisms exists. Since each method has its specific benefits and drawbacks, it remains ambiguous which technique(s) could guarantee stability and sustainability in a cooperative facility location setting. For this reason, an extensive comparative analysis based on an approved statistical technique, applying three different allocation mechanisms to a U.K. case study, is performed in the section 'Experimental design and numerical results'.

The three methods selected in this paper are the Shapley value, the Alternative Cost Avoided Method (ACAM), and the Equal Profit Method (EPM) for the following reasons. First, as current customer-centred facility location literature solves the allocation problem exclusively with game theory, as demonstrated in the section 'The cooperative facility location problem', a comparison with other techniques is interesting to explore. Moreover, basic game theoretic mechanisms may raise questions about mathematical complexity, applicability, fairness transparency, and stability in practice. The most prevalent solution concepts within cooperative game theory are the Shapley value and the nucleolus (Moulin, 1988). The preference for the Shapley value may be explained by its ease of calculation. Applying the Shapley value means evaluating a formula, while finding the nucleolus requires the solution of a series of linear programs. A drawback of using the Shapley value is that, although it guarantees a unique and efficient solution, it does not ensure stability. Of the list of alternative mechanisms discussed in the section `Allocation mechanisms with additional desirable properties', the mechanisms based on the division between separable and non-separable costs developed in Tijs and Driessen (1986) are easy to use and intuitively appealing. Of the three methods proposed, the Equal Charge Method (ECM), the Alternative Cost Avoided Method (ACAM), and the Cost Gap Method (CGM), a preference for the ACAM may be motivated by its transparency, ease of use, and understandability. In addition, the ACAM, as opposed to the ECM, takes into account the different contribution levels of all coalition partners. Finally, in the early phases of a growing horizontal cooperation, it may be beneficial for communication and negotiation purposes to have an initial allocation where the relative benefits of the participating organisations are as equal as possible. For this reason, another desirable property of cooperative cost allocation methods could be that allocations with minimal differences in relative savings of all partners are defined. In this context, Frisk et al (2010) and Liu et al (2010) develop the EPM and the WRSM respectively. Both techniques guarantee stable allocations that minimise the maximum difference between the cost savings allocated to the cooperating partners. The reason for choosing the EPM, as opposed to the WRSM, is twofold. First, Vanovermeire (2014) demonstrates that allocations calculated by means of the EPM satisfy cross-monotonocity in contrast to WRSM allocations. Second, the importance of convenient implementation and interpretation in practice favour the use of the EPM. Based on the above described reasoning for choosing the Shapley value, the ACAM, and the EPM, one could raise the issue that more allocation techniques exist which have been developed for other specific properties in the context of horizontal logistics cooperation. However, it may be stated that most of the remaining techniques cited in the overview are fairly complex to implement in practice or need a significant amount of data which may not be readily available.

The cooperative carrier facility location problem: Mathematical formulation

The cooperative facility location problem handled in this paper can be defined as a multi-company, two-stage, capacitated facility location problem in which multiple sourcing is allowed. The latter means that demand in one customer zone for a particular product type can be fulfilled from more than one DC. It is in essence an extension of the multi-product, capacitated facility location problem, where each product serves a certain given demand in the market and where this product now originates from a specific independent carrier who owns a set of DCs which may or may not be used in the cooperation. For this reason, additional decisions need to be made on a fair cost allocation among participating companies. This topic is discussed in the sections ‘Collaborative cost allocation’ and ‘Experimental design and numerical results’. The supply network considered consists of logistics service providers, labelled carriers, transporting compatible products to multiple customer zones. This transport activity comprises of two stages, namely primary transport from each carrier's central depot to a number of DCs and secondary transport from these DCs to the different customer zones. In Figure 1 an example of a multi-company, two-stage supply network is visualised. Here, carrier A initially owns four DCs. However, consequential to its engagement in a cooperation with carrier B and C, carrier A could also transport its goods to the different customer zones via DCs owned by its partners. The goal of the cooperative facility location model is to share distribution centres between participating carriers with the aim of reducing costs and improving distribution efficiency.

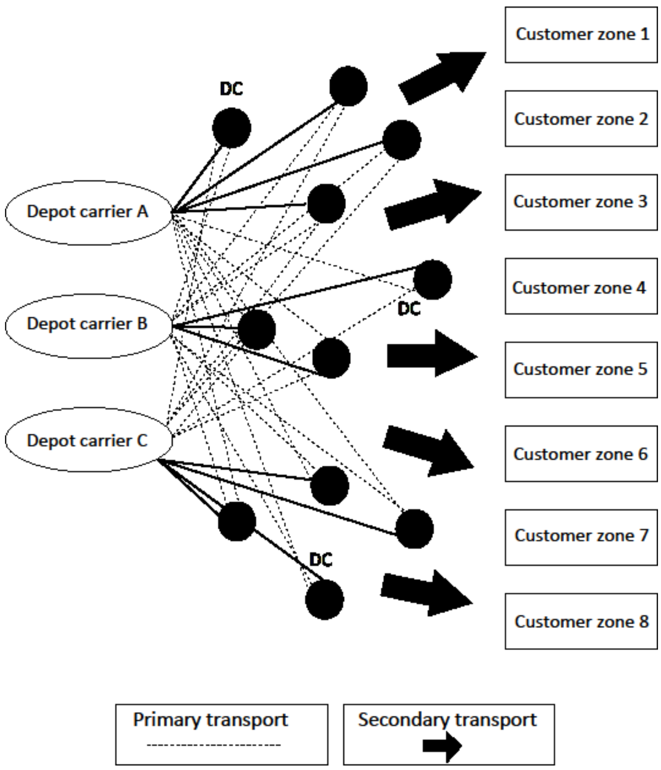

Figure 1 Multi-company two-stage supply network

The following model assumptions are made. Freight transport is modelled in terms of product flows and not in terms of individual vehicles with capacity constraints. This assumption is supported by the practice that carriers are typically able to hire additional third-party transporters. Each carrier has its own central depot from which freight is distributed to DCs and customer zones. Fixed costs, maximum capacities as well as the locations of the DCs are known and the throughput capacity of each DC is constant. The customer zone locations and their demand for transport from each carrier are also known in advance. Each customer zone may be served by more than one DC. The transport cost between carrier depots and DCs is called the primary transport cost and is a linear function of the actual flow of products from the depots to the DCs. Products are transported from DCs to customer zones through secondary transport. In addition to the variable transport costs, costs can be increased to account for the fixed DC-related costs and a local delivery charge for each customer zone, respectively. Since a *cooperative* facility location problem is modelled, all DCs can be supplied by more than one carrier and each DC can supply multiple product units to more than one customer zone. In this way, if a carrier participates in the cooperation, he can share his DCs with the other partnering carriers.

Similarly to traditional facility location problems, the objective is to minimise a total cost function, accounting for both fixed costs of keeping DCs open and all primary and secondary transport costs. The decisions to be taken relate to which cooperative partnership is formed (carrier selection), which DCs to open, and the assignment of product flows. Considering the first decision, it is fixed beforehand which carriers take part in the coalition and allow to share their DCs. As such, the impact of horizontal collaboration may be evaluated for various cooperation structures using an experimental design.

We formulate the problem mathematically as the following mixed integer linear programming problem (MILP), making use of the following notation:

Data	
I	Set of carriers, indexed by i
J	Set of distribution centres, indexed by j
K	Set of customer zones, indexed by k
c_{ijk}	Cost of transporting a single product unit from carrier i to DC j and on to customer k
F_j	Fixed cost of operating distribution centre j
D_{ik}	Demand for products of carrier i in customer zone k
T_j	Capacity or throughput limit of distribution centre j
g_{ij}	Indicator that equals 1 if distribution centre j belongs to carrier i, 0 otherwise
w_i	Indicator that equals 1 if carrier i takes part in the cooperation, 0 otherwise
Decision variables	
z_{ijk}	Total number of product units transported from carrier i to customer zone k via DC j
y_j	Equals 1 if distribution centre j is operational, 0 otherwise

The goal is to open a subset of DCs associated with the cooperating partners. Moreover, for each operational DC, a decision needs to be made on the total number of product units transported from the carriers' central depots to the DC and the total number of product units transported from the DC to the different customer zones. Using the decision variables, our cooperative carrier facility location problem (CCFLP) can be translated into the following mathematical model:

$$Min\, Z = \sum_{j \in J} F_j y_j + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} c_{ijk}\, z_{ijk} \qquad (1)$$

Subject to

$$\sum_{j \in J} z_{ijk} \geq D_{ik}\, w_i \qquad \forall\, k \in K, \forall\, i \in I \qquad (2)$$

$$\sum_{i \in I} \sum_{k \in K} z_{ijk} \leq T_j\, y_j \qquad \forall\, j \in J \qquad (3)$$

$$y_j \leq w_i + 1 - g_{ij} \qquad \forall i \in I, j \in J \qquad (4)$$

$$y_j \in \{0,1\} \qquad \forall j \in J \qquad (5)$$

$$z_{ijk} \geq 0 \qquad \forall i \in I, j \in J, k \in K \qquad (6)$$

The objective function (1) minimises the sum of fixed costs associated with operating DCs and transport costs to distribute products from central depots to DCs and on to customer zones. Constraint set (2) guarantees that the total demand of all customer zones k is satisfied. Constraints (3) ensure that the total amount of product units distributed from carrier depots does not exceed the throughput limit of open DCs. Constraint set (4) reflects the issue of opening and closing DCs when carriers take part in the coalition and want to share facilities. Statement (5) enforces the binary nature of decision variable y_j, while constraints (6) impose non-negativity restrictions on the other decision variable z_{ijk}.

It is worthwhile to note that, for any given set of partners considered or, hence, choice of values for w_i, constraints (4) can be eliminated and the model can be reduced to the classic formulation of a multi-product two-stage capacitated facility location model. As professional commercial MILP solvers eliminate redundant constraints and variables as part of pre-processing a model, there is no real loss of computational efficiency in comparison to building tailored MILP models for each (sub)coalition separately. The current formulation facilitates analysis in that only a single model needs to be constructed and can then be run for various coalitional structures. In addition, this formulation has the advantage in showing explicitly how a change in partners also changes the set of available potential locations for DCs as well as the demand to be satisfied.

The cooperative game corresponding to the CCFLP is superadditive and this is proven as follows. Consider any two disjoint coalitions $S \subseteq N$ and $T \subseteq N$ (where $S \cap T = \emptyset$), and let the optimal objective function value of CCFLP(I) for any coalition $I \subseteq N$ be $Z^* \equiv c(I)$. It then holds that $c(S) + c(T) \geq c(S \cup T)$ since the solution space of CCFLP($S \cup T$) includes the solution spaces of the two disjoint set models CCFLP(S) and CCFLP(T) and therefore (optimal) feasible solutions of these disjoint set models combined also forms a feasible solution for CCFLP($S \cup T$). Unless the companies would operate in completely separated geographical areas, it is also clear that the game will typically be essential, i.e. that $\sum_{i \in I} c(\{i\}) > c(I)$. These two observations imply that the total cost gains from collaboration should increase with the number of participating partners. However, in practice more partners may complicate the process of selecting a cost allocation method that is perceived fair to all partners, and may in addition increase managerial complexity and costs for maintaining the collaborative relationships. Furthermore, in order to share DCs, there must exist compatibility between the types of functions a DC needs to perform for each of the collaborating carriers, which will limit the pool of available partners.

The cooperative carrier facility location model can be expected to lead to particular outcomes that differing from a traditional facility location setting. In the traditional application of facility location models, a large number of potential sites are considered, out of which typically a small number of sites are opened. In a DC sharing context, however, it is assumed that each carrier starts from a set of open DCs of which the number and locations are already (near to) optimal for this carrier when working independently. When considering collaboration, we hence start from this given set of opened facilities, and the model will investigate whether savings can be achieved from collaboration. These savings can only result from either keeping all existing DCs open, but finding a better allocation of transport routes, or from closing a number of DCs and reoptimising the allocation of transport routes.

Mathematically speaking, it is possible to include additional potentially relevant cost components in the CCFLP. This includes any managerial costs, which could be a function of the number of participants in the coalition. However, in this case, the game may no longer be superadditive, and the issue of selecting partners would then account for the trade-off between operational cost and managerial costs. In addition, the model may be extended by including an annuity stream value of proceeds that would be gained from selling a DC when closing it, or by incorporating the possibility that any coalition might want to identify new potential locations to build new (jointly used) DCs. We have refrained from implementing these refinements as the value of collaboration may then be heavily influenced by the one-off revenues or investments. Instead, the model is deliberately kept simple by focussing on the operational fixed and variable costs only, so that the operational value of collaboration between existing carriers can be firmly established.

Cost allocation mechanisms: Description, calculation, and properties

This section describes the three cost allocation techniques selected for their application in the case study. Details are provided on their theoretical foundation and calculation approach.

Cost allocations may satisfy a variety of properties desirable in the context of a horizontal logistics cooperation. Table 2, based on Vanovermeire (2014), provides an outline of allocation characteristics satisfied by the Shapley value, the ACAM, and the EPM respectively.

Table 2 Properties satisfied by Shapley, ACAM, and EPM allocations

Property	Shapley	ACAM	EPM
Group rationality (efficiency)[1]	✓	✓	✓
Individual rationality[2]	✓		✓
Anonymity (symmetry)[3]	✓	✓	✓
Stability[4]			✓
Cross-monotonicity[5]			✓
Dummy[6]	✓		
Additivity[7]	✓		

[1] The total cooperative cost is shared as the grand coalition forms: $\sum_{i \in N} y_i = c(N)$

[2] No carrier pays more than his stand-alone cost: $y_i \leq c(\{i\}), \forall\, i \in N$

[3] The identity of the participants does not change the resulting allocation, each partner gains the same amount when cooperating in the same way with fellow organisations: $c(S \cup i) = c(S \cup j) \rightarrow y_i = y_j$

[4] No single participant or subcoalition of participants of the collaboration would benefit from leaving the grand coalition: $\sum_{i \in S} y_i \leq c(S)$ and $\sum_{i \in N} y_i = c(N)$

[5] When a new player joins the coalition, the allocated benefit of the existing partners should not decrease

[6] Participants, who add zero benefits to the coalition they join, should not be allocated a share of the collaborative savings

[7] The cost allocation of a combination of several separate coalitions is equal to the sum of the separate allocation values of these coalitions: $y(i + j) = y(i) + y(j)$

Shapley value

The Shapley value (Shapley, 1953), a well-known game theoretic method, allocates to each participant the weighted average of his contributions to all (sub)coalitions, assuming the grand coalition is formed one company at a time. The Shapley allocation to participant *i* can be mathematically expressed as:

$$y_i = \sum_{S \subseteq N \setminus \{i\}} \frac{(|S| - 1)!\,(|N| - |S|)!}{|N|!} [c(S \cup i) - c(S)]$$

with |.| denoting the number of participants in the considered (sub)coalition and *c(.)* the cost of the respective (sub)coalition. The Shapley value provides a unique allocation with characteristics that are beneficial in the context of a horizontal logistics cooperation, as visualised in Table 2. However, the Shapley value has an important disadvantage, namely that this allocation may not lie in the core of the game and thus may not lead to a stable collaboration (Krajewska et al, 2008; Frisk et al, 2010; Liu et al, 2010).

Alternative Cost Avoided Method (ACAM)

Tijs and Driessen (1986) present three cost allocation methods based on the division of the total collaborative cost in separable and non-separable costs. The Equal Charge Method (ECM), Alternative Cost Avoided Method (ACAM), and Cost Gap Method (CGM) differ with respect to the weights chosen for the allocation of non-separable costs.

The ACAM defines its weights based on the difference between the individual cost and the marginal cost of each cooperation participant. As such, the ACAM allocation to participant *i* can be mathematically expressed as:

$$y_i = m_i + \frac{c(i) - m_i}{\sum_{j=1}^{n}[c(j) - m_j]} * (c(N) - \sum_{j=1}^{n} m_j)$$

with m_i denoting the separable or marginal cost of company *i,* which may be calculated as $c(N) - c(N \setminus i)$. Similar to the Shapley value, ACAM allocations cannot guarantee stability of the grand coalition, as shown in Table 2.

Equal Profit Method (EPM)

In the early phases of a growing horizontal cooperation, it may be helpful for communication and negotiation purposes to have an initial allocation where the relative benefits of the participating organisations are as similar as possible. For this purpose, Frisk et al (2010) develop the Equal Profit Method (EPM). This profit sharing technique has the goal of finding a stable allocation that minimises the largest relative difference in cost savings between any pair of cooperating partners. Allocation properties satisfied by the EPM are presented in Table 2.

In order to find the EPM allocations to all participants, the following linear program needs to be solved to optimality:

$$Min\ f \qquad (7)$$

Subject to

$$f \geq \frac{y_i}{c(i)} - \frac{y_j}{c(j)} \qquad \forall\ i, j \in N \qquad (8)$$

$$\sum_{j \in S} y_j \leq c(S) \qquad \forall\ S \subseteq N \qquad (9)$$

$$\sum_{j \in N} y_j = c(N) \qquad (10)$$

The first constraint set (8) measures the pair wise difference between the relative savings of the participants. The objective function (7) minimises the largest difference using variable *f*. Constraint sets (9) and (10) ensure that the allocation is stable and belongs to the core. As such, the cost allocation guarantees that no subcoalition S exists in which a set of partners would be better off (9) and the total collaborative cost is shared as the grand coalition forms (10).

Experimental design and numerical results

Although transport companies become increasingly aware of the inevitable character of collaboration, surveys report failure rates from 50 to 70 percent for starting strategic partnerships (Schmoltzi and Wallenburg, 2011). Following this observation, several studies have investigated the conditions influencing the success of horizontal logistics collaboration (e.g. Cruijssen et al, 2007a; Schmoltzi and

Wallenburg, 2011; Audy et al, 2012; Vanovermeire et al, 2013a). To investigate the impact of the collaborative characteristics on attainable savings, the statistical approach of experimental design is very useful. The primary goal of an experimental design is to establish a causal relationship between the independent and dependent variables at hand. This relationship is statistically derived by examining the value of the performance measure associated with various levels of the independent parameters or factors. Lozano et al (2013) and Vanovermeire et al (2013a) have already demonstrated that this statistical technique is suited to analyse the influence of different parameters in a horizontal carrier collaboration setting. The experimental design approach is useful not only for investigating the impact of factor combinations on total cost savings achievable from collaboration, but also for investigating the relative differences between cost allocation methods. According to Cruijssen et al (2007b) and Cruijssen et al (2007c), distrust and doubts about the applied cost or profit allocation mechanisms have caused many horizontal logistics collaborations to break up.

The case study presented in this paper demonstrates the applicability of the CCFLP model and is used as a first exploratory study of this form of horizontal carrier collaboration. The reason for developing an experimental design environment is that, in this way, we are able to study whether the various relationships hypothesised in current collaboration literature between cooperation parameters, collaborative performance, and cost allocation results indeed transfer to a cooperative facility location setting.

The remainder of this section is organised as follows. The subsection ‘Case study’ describes the U.K. case study developed for our numerical analyses. Interested readers are referred to the corresponding author for more details on the case study data. This case study constitutes the basis for the experimental design in the next subsection. The goal of the experimental design is to investigate a number of hypothetical relations introduced in current collaboration literature between cooperation characteristics, collaborative performance, and cost allocation results using an approved statistical technique. For this purpose, the subsection ‘Research hypotheses and experimental design’ presents the hypotheses studied and defines the experimental factors coinciding with the relevant cooperation parameters. Subsequently, the subsection ‘Collaborative cost results’ discusses the relationships between the studied cooperation characteristics and collaborative performance. Next, the effects of applying the Shapley value, the ACAM, and the EPM are analysed and compared to their respective hypotheses in the subsection ‘Cost allocation results’.

Case study

Extensive numerical experiments are performed on a case study consisting of an artificial set of carriers distributing similar products in two phases (see Figure 1) and employing multiple sourcing. Three carriers A, B and C with their central depots located in Scotland, London and Wales, respectively, distribute products in two phases (as in Figure 1). We assume them to distribute products which are compatible in that they require a similar type of DC. These carriers can hence embark on a project whereby they would share their DCs. The ownership and location of all DCs, central depots, and customer zones are visualised in Figure 2. Fixed costs and maximum capacities of the 10 DCs are known, as well as primary and secondary transport costs. Transport demand stems from 10 different customer zones representing large geographical areas in the U.K. and is also known beforehand.

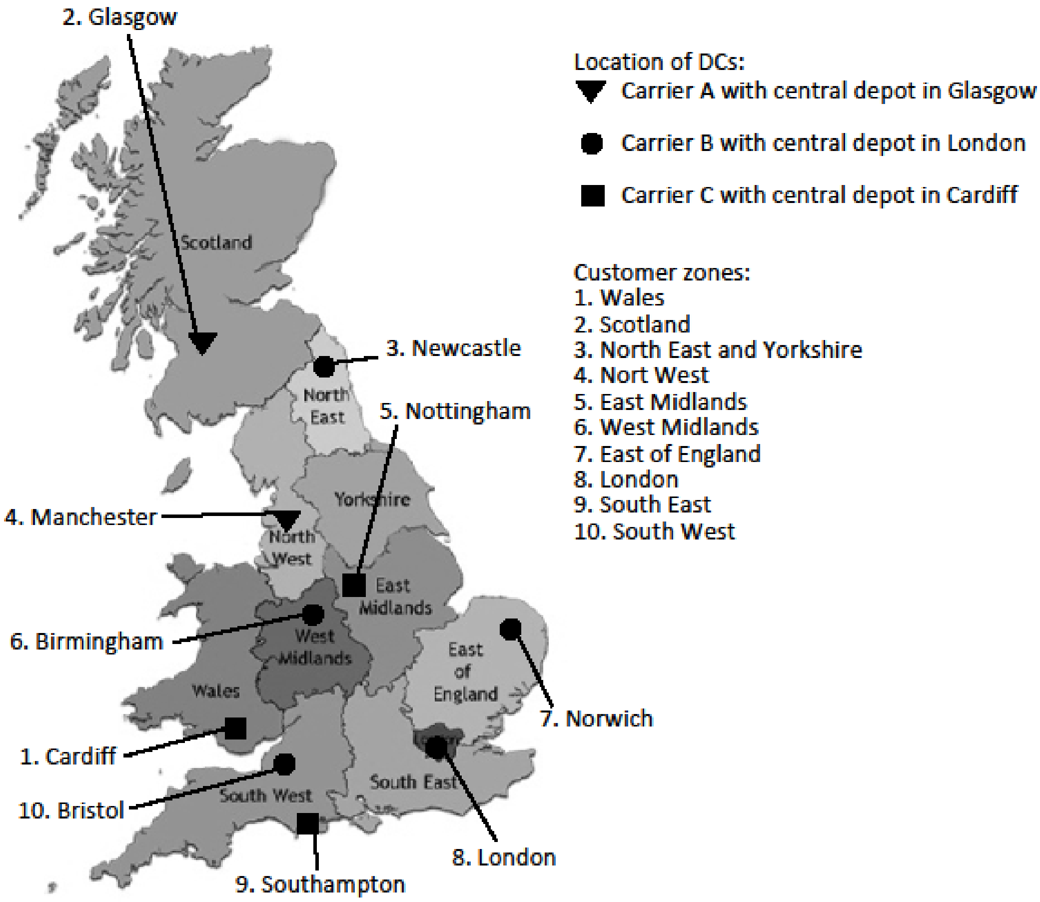

Figure 2 Geographic locations of central depots, DCs, and customer zones for carriers A, B and C.

While the case study data used in our analyses is fictitious, its numerical values are based on real logistics settings in the U.K. Numerical values for transport costs are based on travel distances on the U.K. road network, fuel and driver wages, and average speeds derived from legal speed limits. In addition, variable operating costs at DCs and customer demand points can be added to the transport costs in the CCFLP model. The fixed costs levels at DCs depend on the functions of a DC and the associated level of automation needs for e.g. storage and retrieval, order picking, and order tracking. While high levels of investment in automation increase fixed costs, they may also reduce the overall variable operating costs at the DC leading to an increased contribution of fixed costs relative to variable costs. Because of the resulting variation in relative levels of fixed and variable DC cost components, we have calibrated the fixed cost data towards being able to represent two extreme situations. In the first situation, the total DC costs of carriers not cooperating constitutes approximately 50% of the total transport costs. In the other situation, total transport costs in the case of no cooperation are 50% of the total DC costs. According to our own experience, most realistic settings fall within these two boundaries, see also Zollinger (2001) and Rantasila and Ojala (2012).

Research hypotheses and experimental design

In line with statements made in current scientific literature, the following research hypotheses are analysed here in a cooperative facility location setting. First, transport companies may be obliged to work under different settings of DC costs relative to transport costs. As such, we examine whether collaborative performance is sensitive to the two extreme situations introduced earlier with respect to this ratio. Second, according to Verstrepen (2005) and Schmoltzi and Wallenburg (2011), broad geographic coverage constitutes an important aspect of collaborative gains and sustainability. We hence investigate whether an increased number of served customer zones has a positive impact on attained collaborative savings, and whether it improves stability. Third, Park and Russo (1996) and Griffith et al (1998) found in their general joint venture setting that the number partners affects collaborative performance in a positive way. Since the game associated with the CCFLP is superadditive and often essential, as discussed earlier, we may expect this to hold in our case study. However, this does not guarantee coalition stability, and we will hence investigate whether larger coalitions can offer this stability or not in our DC sharing context. Fourth, in line with the operational fit concept described by Verstrepen (2005), the impact of similarity of collaborating companies on alliance performance is studied. The level of equality of firms is measured in terms of the fraction of total demand each carrier needs to serve and the relative number of DCs a carrier contributes to the coalition. As such, a comparison of gains achievable when changing the initial level of market consolidation across participating carriers could be made. Finally, as DC sharing affects both the location of opened DCs and the allocation of transport flows, and given the increased attention for environmental impacts of transport (emissions, congestion), we investigate how DC sharing affects total transport cost and distance travelled.

As in Law (2007), a 2^4 factorial design is developed. In this way, the main and interaction effects of four factors can be derived by examining the value of the dependent variable associated with each of the two factor levels, labelled “+1” (high) and “-1” (low). Following the research hypotheses discussed above, the experimental factors or cooperation characteristics considered in our analysis, are: fixed DC costs (F1), number of served customer zones (F2), number of participating carriers (F3), and degree of inequality of participating carriers (F4). In Table 3 an overview is provided of studied cooperation characteristics and their associated level values. With respect to the factor ‘Fixed DC costs’, level “+1” is equal to the level “-1” fixed DC cost multiplied by five. With this multiplication, the effect of a sufficiently large difference in fixed DC costs relative to transport costs, and approximately capturing the 50% ratios discussed earlier, can be investigated. Concerning level “-1” of factor two, the customer zones not considered are North East and Yorkshire (3), West Midlands (6), South East (9), and South West (10). The reason for choosing to ignore these four customer zones is their significance in the distribution activities of the considered carriers. Leaving out customer zones that only represent a small fraction of customer demand would not sufficiently influence collaborative performance. With regards to factor three, carrier A is left out in the two-partner coalition. Leaving out carrier B or C would lead to insufficient DC capacity to cope with total customer demand. It is important to point out that in the B and C two-partner instances, the demand of carrier A is reallocated to B and C, while the DCs that belong to carrier A are eliminated from the set of potential

DCs available to B and C. In this way, the influence of the level of consolidation in the carrier market could be studied. The factor ‘Degree of inequality’ is measured in terms of DC ownership and demand distribution of partnering carriers. As such, ‘Equal’ carriers in a two-partner coalition each own 50% of all DCs and are responsible for the same percentage of demand. On the contrary, ‘Different’ partners own 30% and 70% of all DCs respectively and execute the same amount of customer zone orders. In a three-partner coalition, ‘Equal’ carriers each own approximately 33.33% of all DCs and serve 33.33% of demand. ‘Different’ partners own 20%, 30%, and 50% of all DCs respectively and account for the same amount of customer demand.

Table 3 Experimental factors and their associated levels

Factor	Level -1	Level +1
1. Fixed DC costs	Low	High
2. Number of customer zones	6	10
3. Number of carriers	2	3
4. Degree of inequality	Equal	Different

Based on these factor levels, 16 experiments, coinciding with different cooperation settings, are created. In ‘Appendix A’, Table 5 lists all studied experiments and the factor levels they are associated with.

In the next sections ‘Collaborative cost results’ and ‘Cost allocation results’ the collaborative cost levels and the allocation values are analysed and compared respectively over all 16 scenarios associated with the full factorial design described above. Concerning the conclusions drawn in these two sections, we want to emphasise that they only apply to the developed experimental design. However, reviewing current literature reveals that the results presented here display clear similarities with conclusions drawn in other logistics collaboration contexts (e.g. Verstrepen, 2005; Schmoltzi and Wallenburg, 2011; Vanovermeire et al, 2013a; Vanovermeire et al, 2013b).

Collaborative cost results

After applying the cooperative facility location model CCFLP, given by equations (1)-(6), to all factor combinations of our case study with the use of LINGO 10.0 software, we now analyse its main results. These results define a minimum cost solution through the identification of the optimal number of operational DCs, the optimal product flows between the central carrier depots and these DCs, and the optimal allocation of DCs to customer zones. Table 4 compares fixed DC costs and transportation costs (in k€) with and without cooperation for all collaborative experiments.

Table 4 Cost results (in k€) with and without cooperation for all experiments

Experiment	**No cooperation**		**Grand coalition**	
	Fixed DC costs	*Transportation costs*	*Fixed DC costs*	*Transportation costs*
1	2713.2	5241.0	2441.2	5084.0
2	12206.0	5912.3	11704.5	5190.2
3	2713.2	4949.2	2340.9	4706.0
4	12435.5	5628.4	11704.5	4706.0
5	2487.1	5987.1	2441.2	5703.7
6	12325.0	6023.0	11194.5	6060.2
7	2509.2	5850.9	2238.9	5826.9
8	12325.0	5918.5	11194.5	5826.9
9	2441.2	6468.7	2340.9	5020.6
10	12206.0	6468.7	11704.5	5020.6
11	2487.1	6305.7	2340.9	4551.3
12	12435.5	6305.7	11704.5	4551.3
13	2713.2	5540.9	2441.2	5330.6
14	13566.0	5540.9	11194.5	5787.0
15	2713.2	5355.3	2441.2	5200.4
16	13566.0	5355.3	11194.5	5486.0

The savings level associated with cooperative facility location ranges from 3.52% to 21.62% over all experiments, with an average savings level of 9.1%. Horizontal collaboration through DC sharing can hence produce large operational benefits to carriers. However, because of the wide spread in possible savings, and because 3.52% may not be a sufficient gain to compensate for additional overheads of collaboration (which are not accounted for in these experiments), a further investigation of the main effects of the four factors on the synergy attained by the collaboration is in order.

Concerning the **fixed DC costs**, results demonstrate that the amount of fixed costs has a modest positive effect on the collaborative savings level. Moving factor one from its “-1” level to its “+1” level, while holding all other factors fixed, leads to an average increase of savings by 0.53%. Collaboration incentives thus improve if carriers are faced with heightened DC investments, but much less so then one might initially expect. The reason for this can be found in the particular nature of collaborative DC sharing, which differs from the setting of a traditional facility location problem in that the number of available DCs is restricted to those DCs each carrier is already using. Because DCs are probably designed with a fairly small slack in excess capacity for each carrier, DC sharing can be expected not to produce the closure of many existing DCs, and hence the level of fixed DC costs will have little impact on attainable savings. In our experiments collaboration has the effect of closing on average about 1 DC only.

The **number of customer zones** influences the attained savings in a positive way. Serving 10 customer zones instead of 6 adds, on average, 1.58% to the collaborative savings level, leaving all other cooperation characteristics unchanged. Increased geographical coverage can provide more cooperation opportunities and could thus lead to larger cost reductions. The value of broad geographical coverage in terms of potential savings, discussed by Verstrepen (2005) and Schmoltzi and Wallenburg (2011) in a general logistics collaboration context, is thus confirmed in a cooperative facility location environment.

On the contrary, the findings of Park and Russo (1996) and Griffith et al (1998) that the number of partners in a joint venture influences its performance in a positive way can be expounded upon in a cooperative facility location setting. As discussed earlier in the section introducing the CCFLP model, we should expect that including more partners increases total savings achieved. For this, we cannot however compare based on factor 3 levels, but need to look at the characteristic cost function values of subcoalitions in the experiments of three carriers, as in e.g. Table 10 and Table 11 (Appendix C). Analysing these results reveals that no subcoalition can do equally well or better than the grand coalition. In this sense, economies of scale as intended in Park and Russo (1996) and Griffith et al (1998) also apply in a cooperative facility location context. However, with respect to our third factor, Table 4 shows that **the number of coalition partners** affects the amount of collaborative savings in a negative way when considering a DC sharing coalition. As such, a two-partner coalition will enjoy cost savings that are on average 4.73% higher than those of a collaboration with three partners. If the market is more consolidated such that two carriers serve the same total demand rather than three carriers, and despite having access to less potential DC sites, collaboration in the two carrier market setting thus leads to significantly higher cost savings. Collaborating with a limited number of partners also reduces alliance complexity and may enforce the strength of mutual partner relationships.

Finally, the factor **degree of inequality** shows the largest positive impact on realised cost reductions. A coalition with partners differing in terms of DC ownership and demand distribution will gain on average 5.92% more than a partnership comprised of fairly equal participants. As partner differences may complement or supplement each other, the number of possible improvement opportunities could increase. This is compatible with the results by Vanovermeire et al (2013a) in an order consolidation context, who found that shippers differing in average order size and/or number of orders leads to better results in terms of collaborative profit in a significant amount of cases. While these findings indicate that the overall relative gains achievable may be greater when firms are complementary on the one hand, Verstrepen et al (2009) advise on the other hand that it is better to select partners of approximately similar size and market power in order to avoid unilateral dominance when it comes to cost sharing arrangements. Our findings hence underline an important dilemma between total cost savings achievable, which are higher with the degree of inequality rising, versus the practical implementation of fair allocations of total gains, which may be hampered with a rising degree of inequality between carriers.

With respect to the **impact of DC sharing on transport**, results demonstrate that jointly and optimally deciding on the location of DCs and the allocation of product flows not only reduces total logistics costs, but is likely to also improve transport efficiency. It is clear that this is in general not necessarily true, in particular when as a result of collaboration many DCs would be closed. We assume however that most DC sharing partnerships will start from a similar situation as in our experiments whereby as a result of the collaboration a relatively small number of DCs will close. The average decrease in transport costs is 17.9% for our case study. In 13 out of 16 experiments, sharing DCs with fellow transport companies decreases both fixed DC costs and transport costs (see also Table 4). The three cases where transport costs increase are, as expected, all for situations where the fixed DC costs are high, as this stimulates the closure of DCs and thus could increase transport costs as a result. As such, cooperative facility location does not only benefit participating carriers but quite likely also society as a whole in terms of reduced congestion and CO_2 emissions.

Besides main effects, two-way interactions between experimental factors were also investigated. Numerical analysis of these figures revealed, however, that no general insights could be formulated.

Cost allocation results

In order to ensure sustainability of the cooperation project, incurred logistics costs need to be divided in a fair way among the participants. For this reason, the collaborative costs, calculated by means of the proposed CCFLP, are now allocated to the carriers applying the Shapley value, the Alternative Cost Avoided Method (ACAM), and the Equal Profit Method (EPM). For detailed results, interested readers are referred to 'Appendix B'.

To identify whether the cost allocations defined for the case study experiments guarantee cooperation **stability**, compliance of the Shapley and ACAM solution with individual, subgroup, and group rationality needs to be verified. A cost allocation satisfying the *individual rationality* property guarantees that no carrier pays more than his stand-alone cost: $y_i \leq c(\{i\}), \forall\ i\ \in N.$ *Subgroup rationality* will avoid players leaving the grand coalition to form a subgroup because they could be better off excluding certain partners: $\sum_{i \in S} y_i\ \leq c(S), \forall\ S\ \subseteq N$. *Group rationality*, also labelled efficiency, ensures that the total cooperative cost is shared as the grand coalition forms: $\sum_{i \in N} y_i\ = c(N)$. Since core constraints are included in the EPM linear program, feasibility of the EPM solution immediately indicates whether the grand coalition is stable. In case of a non-stable grand coalition, additional allocations ("Stability relaxation EPM" and "ε-EPM") are listed. Regarding the calculation of these cost allocations for non-stable collaborations, two modifications have been applied to the EPM in order to find a feasible solution. First, allocation values have been calculated while relaxing core constraints that could not be satisfied for the respective cooperative game. Second, EPM has been combined with the ε-core concept, as suggested by Frisk et al (2010). Applying the ε-core, cooperation participants are penalised with a cost $\varepsilon > 0$ for quitting the grand coalition. In this way, stable cost allocations may be calculated for cooperative games with an empty core (Shapley and Shubik, 1966). As an example, in 'Appendix C' stability conditions are examined for Shapley, ACAM, and EPM allocations calculated for experiments 5 and 15.

Analysing cost allocations over all experiments reveals that **stability** of the grand coalition is guaranteed in 14 out of 16 experiments. In the remaining two collaboration scenarios (experiments 13 and 15) the core of the cooperative game is empty. If the grand coalition is stable, then no subgroup of partner companies has the incentive to leave the grand coalition and be better off acting alone. We found that in the experimental design stability either holds or not, i.e. that this outcome is independent of the allocation technique used. The non-stable cooperation structures demonstrate the influence of DC fixed costs to the decisions made by cooperating carriers. Results show that, while high DC costs are always related with stable outcomes, a low level of fixed DC costs is only associated with coalition stability if the collaboration consists of two partners and/or the partners are equal. As such, if transport companies decide to share their DCs with more than one organisation and/or their collaboration partners differ in terms of operational resources, long-term coalition sustainability is more likely if the DC operations require a high level of investments. In addition, we found no evidence to support the recommendations from Verstrepen (2005) and Schmoltzi and Wallenburg (2011) that a larger geographical coverage improves coalitional stability for the DC sharing context.

Investigating the allocation values defined by means of the Shapley value, the ACAM, and the EPM variations over all experiments, the following observations can be made. First, **differences** between 0% and 5.32% exist in the allocation values when comparing over the **division mechanisms**. The share of logistics costs allocated to the cooperation participants is thus fairly similar with respect to the used allocation technique. The smallest differences are associated with coalitions between equal partners, the largest differences emerge when partners are unequal. For all two-partner coalitions, Shapley and ACAM lead to identical cost allocations, regardless of the degree of equality between both carriers. Similar results were found by Vanovermeire et al (2013b) in a collaborative order consolidation context. Second, examining the **cost share allocated to the different cooperation participants** reveals that the allocation of cost savings is related to the cooperation structure, regardless of the used division mechanism. As such, in two-partner coalitions consisting of *equal* carriers, collaborative cost savings are almost equally divided among both companies, irrespective of possible differences in partner contributions in terms of DC closure and/or changes made in distribution activities consequential to the set-up of the collaboration. On the contrary, in three-partner coalitions comprised of *equal* participants, the highest share of collaborative savings is allocated to the organisation that has contributed most to the partnership. For example, in experiment seven carrier B receives up to 5.11% of collaborative cost savings while carrier A and C enjoy cost savings up to 3.47% and 3.80% respectively. The explanation for this result may be found in the design of the collaborative product distribution network connecting carrier depots, DCs and customer zones. Due to the establishment of the collaborative facility location project, the London DC, owned by carrier B, is closed to save on total logistics cost. As a consequence, because this DC is also the location of the central depot (or factory), carrier B had to make the most profound changes in its distribution activities. The allocation techniques account for these contributions by rewarding carrier B with the highest share in the collaborative savings. Then, investigating coalition values for collaborations comprised of *different* partners, results demonstrate that the largest partner receives the smallest share of the total collaborative savings level both in two-partner and three-partner coalitions. The explanation for this result can again be found in the contributions made by the participating carriers. In the majority of the experiments with different cooperation participants, the DCs that are closed consequential to the implementation of cooperative facility location are owned by small carriers. Third, the original EPM and the EPM with relaxed stability constraints provide the **most equally spread cost savings** among the partners of the coalition. Especially when fixed DC costs are low or coalitions consist of only two partners, differences between costs allocated to coalition participants are minimal. Although the ε-EPM also aims to minimise maximal pair wise differences between allocated savings, increased variation in carrier savings is caused by adding ε-core constraints. Finally, it is found that the **Shapley value slightly benefits small carriers** in case of a three-partner coalition with different participants. On average, collaborative savings of companies with a smaller share in customer demand are highest when costs are divided by means of the Shapley value. A similar result was found by Vanovermeire et al (2013b) in a collaborative order consolidation context.

Conclusions and future research

Horizontal collaboration between logistics service providers is an important research area given the highly competitive environment in which carriers need to operate. In this paper we study horizontal carrier collaboration at the level of sharing warehouses or distribution centres. This extends the literature on quantitative modelling of horizontal carrier collaboration which has focussed mostly on the sharing of orders and vehicle capacity in a vehicle routing context.

The problem considered can be classified as a cooperative carrier facility location problem and can be formulated as a mixed integer linear program CCFLP. The CCFLP formulation presented models the cooperative carrier facility location problem as a multi-commodity, two-phase, location-allocation problem. The practical advantage of the CCFLP exists in that the model and data is to be prepared a single time only, and is then easy to use for deriving the optimal location-allocation decisions and characteristic function values for each possible (sub)coalition. The CCFLP presented in this form also has the benefit of clearly showing that the decision problem differs from current cooperative facility location literature in that the number of potential DC locations as well as the customer demand changes with the choice of partners in the coalition. In addition, the allocation of costs is not to be between the customers served, but between the participating carriers, and issues of complementarity and selection of partner carriers become important. The CCFLP formulation facilitates the investigation of partner selection. Moreover, to ensure cooperation sustainability, the collaborative costs need to be allocated to the different participants in such a manner that the firms have no incentive to leave the coalition and that the distribution of savings is considered fair. In current cooperative facility location literature the allocation problem is solved exclusively by applying game theory. The rationale of applying alternative cost allocation techniques in the context of carrier collaboration has been discussed, and we have tested the Alternative Cost Avoided Method (ACAM) and the Equal Profit Method (EPM).

We conduct an experimental design around a U.K. based case study to investigate the benefits of collaboration at the level of DC sharing, and compare the findings with general recommendations found in existing horizontal carrier collaboration literature. Our results demonstrate that jointly and optimally deciding on the location of DCs and the allocation of product flows not only reduces total logistics costs in a range from 3.5% to almost 22%, but is very likely to also decrease total kilometres driven. Sharing DCs can hence introduce significant savings in total distribution costs, and is likely to have a positive environmental impact. Our results also indicate that benefits from DC sharing depend on operational characteristics of the partners. The relative level of fixed DC costs and geographical demand coverage have a limited positive impact on collaborative performance, which is in line with previous recommendations from collaboration literature. We have elaborated on the statement made in joint venture literature that more partners create more savings. Economies of scale hold in the sense that subcoalitions cannot achieve higher total savings than the grand coalition. In addition, we investigated how the initial level of consolidation in the carrier market influences collaborative savings. This factor has, to our knowledge, not been investigated previously. Our experiments indicate that the virtual firm comprising of three smaller carriers may not be able to outcompete the virtual firm comprising of two larger carriers serving the same demand, since savings are on average 4.7% higher for a collaboration between two larger carriers, despite having less DC sites available. Regarding partner selection, existing literature states that, from a practical point of view, it may be best to choose partners equal in resources and growth possibilities. However, in the context of DC sharing we found that value lies in partner complementarity. A coalition of unequal partners will gain on average almost 6% more savings than a coalition of equal partners. This factor is also the most significant in explaining the differences between cost savings of various cooperation structures, and hence underlines the importance of partner selection. As such, our findings indicate an important dilemma between total cost savings achievable from horizontal carrier collaboration, which are higher with the degree of inequality rising, versus the practical implementation of fair allocations of total gains, which may be hampered with a rising degree of inequality between the carriers.

When participants have to decide on the mechanism of how to share collaborative savings, the following insights may be formulated. For two- and three-partner collaborations comprised of unequal partners and for three-partner alliances between equal carriers, allocation techniques account for differences in partner contributions to the grand coalition. For coalitions consisting of only two partners, however, Shapley and ACAM lead to identical splits of total gains, and also EPM is not that far from this outcome when partners are equal. The original EPM and the EPM with relaxed stability constraints may be most useful in collaborations between carriers of equal size as they provide the most equally spread cost savings. In addition, this characteristic may also be valuable in the early phases of a growing horizontal cooperation, in which having an initial allocation with similar benefits for all participating organisations may suit communication and negotiation purposes. Small carriers participating in three-partner coalitions may prefer costs to be allocated by means of the Shapley value. This division mechanism favours companies with a smaller share in customer demand by allocating them a higher percentage of collaborative savings in comparison to the ACAM and the EPM. Next, results show that although the magnitude of fixed costs associated with operating a DC does not have a very significant impact on total cost savings achievable, this factor may have a more significant influence on cooperation stability. The case study results demonstrate that higher levels of DC costs are likely to lead to more coalition sustainability. Finally, the most striking finding is that relatively small differences where observed in the allocation values when comparing over the division mechanisms. This may not be so, however, when considering coalitions of more partners.

Overall, our experiments suggest that with a limited number of partners, if chosen carefully, carriers may reap significant operational benefits from DC sharing. A small number of coalition participants has practical benefits in terms of keeping managerial and communication efforts within limits. Furthermore, for a limited number of partners, intuitively appealing and operationally simple cost sharing techniques at the level of DC sharing may well be utilised, which could reduce alliance complexity and enforce the strength of mutual partner relationships. We acknowledge the limitations of our experimental study in terms of general validity of these findings. These conclusions, together with our observation that gains achievable can range between a few percent to well over 20% in our experiments, however underline the value of using operational research models such as the CCFLP presented to help carriers investigate the value of careful partner selection.

Several opportunities for future research on the cooperative carrier facility location problem may be identified. One natural avenue of research is to consider other cost allocation techniques from the literature and to extend the analysis to more partners. Second, in order to establish the logistics benefits of horizontal collaboration, we have excluded the consideration of possible gains from selling closed DCs or building new additional DCs in a coalition, but it is possible to extend the presented MILP in order to consider such opportunities. Finally, the cooperative facility location model could be expanded by considering additional objectives besides cost minimisation. In this way, the trade-off between cost savings versus customer service levels achievable as a consequence of DC sharing could be investigated, for example.

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Appendix A

Table 5 Experiments of full factorial design

Experiment	Factor 1	Factor 2	Factor 3	Factor 4
1	-1	-1	-1	-1
2	+1	-1	-1	-1
3	-1	+1	-1	-1
4	+1	+1	-1	-1
5	-1	-1	+1	-1
6	+1	-1	+1	-1
7	-1	+1	+1	-1
8	+1	+1	+1	-1
9	-1	-1	-1	+1
10	+1	-1	-1	+1
11	-1	+1	-1	+1
12	+1	+1	-1	+1
13	-1	-1	+1	+1
14	+1	-1	+1	+1
15	-1	+1	+1	+1
16	+1	+1	+1	+1

Appendix B

In Tables 6 to 9, cost allocation values (in k€) according to the Shapley value, the ACAM, and the EPM are shown for all carriers over all experiments. The column “Individual” presents the standalone logistics costs. For the EPM, additional calculations (“Stability relaxation” and “ε-EPM”) have been performed in the case of stability issues with the EPM result, as explained in the subsection ‘Cost allocation results’.

Table 6 Cost allocation results (in k€) for *two-partner coalitions with equal carriers*

Carrier	Individual	Shapley	ACAM	EPM		
				Original	*Stability relaxation*	*ε-EPM*
Experiment 1						
B	3653.0	3438.5	3438.5	3455.9	n.a.	n.a.
C	4301.3	4086.8	4086.8	4069.3	n.a.	n.a.
Total	7954.2	7525.2	7525.2	7525.2	n.a.	n.a.
Experiment 2						
B	8807.4	8195.6	8195.6	8212.6	n.a.	n.a.
C	9310.9	8699.1	8699.1	8682.1	n.a.	n.a.
Total	18118.3	16894.7	16894.7	16894.7	n.a.	n.a.
Experiment 3						
B	3557.6	3249.8	3249.8	3271.8	n.a.	n.a.
C	4104.8	3797.1	3797.1	3775.1	n.a.	n.a.
Total	7662.4	7046.9	7046.9	7046.9	n.a.	n.a.
Experiment 4						
B	8712.0	7885.2	7885.2	7914.5	n.a.	n.a.
C	9352.0	8525.2	8525.2	8496.0	n.a.	n.a.
Total	18063.9	16410.5	16410.5	16410.5	n.a.	n.a.

Table 7 Cost allocation results (in k€) for *three-partner coalitions with equal carriers*

Carrier	Individual	Shapley	ACAM	EPM		
				Original	*Stability relaxation*	*ε-EPM*
Experiment 5						
A	3240.7	3192.8	3201.2	3171.1	n.a.	n.a.
B	2441.5	2288.6	2282.7	2320.4	n.a.	n.a.
C	2792.0	2663.5	2661.0	2653.4	n.a.	n.a.
Total	8474.2	8144.9	8144.9	8144.9	n.a.	n.a.
Experiment 6						
A	6266.7	6101.9	6216.0	6202.2	n.a.	n.a.
B	6073.0	5418.6	5252.9	5327.4	n.a.	n.a.
C	6008.4	5734.2	5785.8	5725.1	n.a.	n.a.
Total	18348.0	17254.7	17254.7	17254.7	n.a.	n.a.

Experiment 7						
A	3358.3	3280.7	3285.8	3241.7	n.a.	n.a.
B	2422.6	2303.8	2298.8	2336.5	n.a.	n.a.
C	2579.2	2481.2	2481.3	2487.6	n.a.	n.a.
Total	8360.1	8065.8	8065.8	8065.8	n.a.	n.a.
Experiment 8						
A	6384.3	6193.6	6286.2	6246.9	n.a.	n.a.
B	6063.6	5378.2	5259.3	5426.8	n.a.	n.a.
C	5795.6	5449.7	5475.9	5347.7	n.a.	n.a.
Total	18243.5	17021.4	17021.4	17021.4	n.a.	n.a.

Table 8 Cost allocation results (in k€) for *two-partner coalitions with different carriers*

Carrier	**Individual**	**Shapley**	**ACAM**	**EPM**		
				Original	*Stability relaxation*	*ε-EPM*
Experiment 9						
B	5251.1	4476.9	4476.9	4338.5	n.a.	n.a.
C	3658.8	2884.6	2884.6	3023.0	n.a.	n.a.
Total	8909.9	7361.5	7361.5	7361.5	n.a.	n.a.
Experiment 10						
B	11629.5	10654.7	10654.7	10415.4	n.a.	n.a.
C	7045.2	6070.4	6070.4	6309.7	n.a.	n.a.
Total	18674.7	16725.1	16725.1	16725.1	n.a.	n.a.
Experiment 11						
B	5009.1	4058.8	4058.8	3926.3	n.a.	n.a.
C	3783.8	2833.5	2833.5	2965.9	n.a.	n.a.
Total	8792.8	6892.2	6892.2	6892.2	n.a.	n.a.
Experiment 12						
B	11571.1	10328.4	10328.4	10036.5	n.a.	n.a.
C	7170.2	5927.5	5927.5	6219.3	n.a.	n.a.
Total	18741.2	16255.8	16255.8	16255.8	n.a.	n.a.

Table 9 Cost allocation results (in k€) for *three-partner coalitions with different carriers*

Carrier	Individual	Shapley	ACAM	EPM		
				Original	*Stability relaxation*	*ε-EPM*
Experiment 13						
A	2060.8	1930.3	1963.1	Infeasible	1940.4	1960.5
B	3653.0	3516.2	3542.3	Infeasible	3439.5	3540.3
C	2540.3	2325.2	2266.3	Infeasible	2391.9	2271.0
Total	8254.1	7771.8	7771.8	n.a.	7771.8	7771.8
Experiment 14						
A	4454.4	3806.8	3857.9	3821.2	n.a.	n.a.
B	8807.4	8153.6	8199.4	8146.2	n.a.	n.a.
C	5845.1	5021.1	4924.2	5014.1	n.a.	n.a.
Total	19106.9	16981.5	16981.5	16981.5	n.a.	n.a.
Experiment 15						
A	2144.8	2041.7	2090.3	Infeasible	2031.3	2080.9
B	3557.6	3400.7	3382.7	Infeasible	3369.4	3386.2
C	2366.1	2199.2	2168.7	Infeasible	2240.9	2174.5
Total	8068.5	7641.6	7641.6	n.a.	7641.6	7641.6
Experiment 16						
A	4538.4	3861.3	3905.5	3934.5	n.a.	n.a.
B	8712.0	7981.1	7991.2	7829.8	n.a.	n.a.
C	5670.9	4838.1	4783.7	4916.2	n.a.	n.a.
Total	18921.3	16680.5	16680.5	16680.5	n.a.	n.a.

Appendix C

As demonstrated in Table 10, both Shapley and ACAM allocations satisfy all rationality conditions for experiment 5. Stability of the grand coalition can thus be guaranteed. On the contrary, stability cannot be guaranteed for the grand coalition of experiment 15 (Table 11). Carriers will have the incentive to leave the grand coalition since operating in certain subgroups is associated with lower logistics costs.

Table 10 Stability of cost allocation results (in k€) for experiment 5

	Coalition	Cost allocation y_i		Cost level *c(.)*
Shapley				
Individual rationality	{A}	3192.8	≤	3240.7
	{B}	2288.6	≤	2441.5
	{C}	2663.5	≤	2792.0
Subgroup rationality	{A,B}	5481.3	≤	5583.5
	{A,C}	5856.3	≤	5983.0
	{B,C}	4952.1	≤	4973.8
Group rationality	{A,B,C}	8144.9	=	8144.9
ACAM				
Individual rationality	{A}	3201.2	≤	3240.7
	{B}	2282.7	≤	2441.5
	{C}	2661.0	≤	2792.0
Subgroup rationality	{A,B}	5483.9	≤	5583.5
	{A,C}	5862.2	≤	5983.0
	{B,C}	4943.7	≤	4973.8
Group rationality	{A,B,C}	8144.9	=	8144.9

Table 11 Stability of cost allocation results (in k€) for experiment 15

	Coalition	Cost allocation y_i		Cost level *c(.)*
Shapley				
Individual rationality	{A}	2041.7	≤	2144.8
	{B}	3400.7	≤	3557.6
Subgroup rationality	{C}	2199.2	≤	2366.1
	{A,B}	5442.4	≤	5451.9
	{A,C}	**4240.9**	**≥**	**4240.3**
	{B,C}	**5599.9**	**≥**	**5545.5**
Group rationality	{A,B,C}	7641.6	=	7641.6
ACAM				
Individual rationality	{A}	2090.3	≤	2144.8
	{B}	3382.7	≤	3557.6
	{C}	2168.7	≤	2366.1
Subgroup rationality	{A,B}	**5473.0**	**≥**	**5451.9**
	{A,C}	**4258.9**	**≥**	**4240.3**
	{B,C}	**5551.3**	**≥**	**5545.5**
Group rationality	{A,B,C}	7641.6	=	7641.6

Stability relaxation EPM				
Individual rationality	{A}	2031.3	≤	2144.8
	{B}	3369.4	≤	3557.6
	{C}	2240.9	≤	2366.1
Subgroup rationality	{A,B}	5400.7	≤	5451.9
	{A,C}	**4272.3**	**≥**	**4240.3**
	{B,C}	**5610.3**	**≥**	**5545.5**
Group rationality	{A,B,C}	7641.6	=	7641.6
ε-EPM				
Individual rationality	{A}	2080.9	≤	2144.8
	{B}	3386.2	≤	3557.6
	{C}	2174.5	≤	2366.1
Subgroup rationality	{A,B}	**5467.1**	**≥**	**5451.9**
	{A,C}	**4255.5**	**≥**	**4240.3**
	{B,C}	**5560.7**	**≥**	**5545.5**
Group rationality	{A,B,C}	7641.6	=	7641.6