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Allocating collaborative costs in multimodal barge networks for freight bundling

Katrien Ramaekers[1,*], Lotte Verdonck[1,2], An Caris[1], Dries Meers[3], and Cathy Macharis[3]

[1]Universiteit Hasselt, Agoralaan - building D, 3590 Diepenbeek, Belgium

[2] Research Foundation Flanders (FWO), Egmontstraat 5, 1000 Brussels, Belgium

[3] Vrije Universiteit Brussel, Research Group MOBI, Pleinlaan 2, 1050 Brussels, Belgium

[*]*Corresponding author at*: Universiteit Hasselt, Campus Diepenbeek, Agoralaan - building D, 3590 Diepenbeek, Belgium. Tel.: +32 (0)11269151.
E-mail addresses: katrien.ramaekers@uhasselt.be, lotte.verdonck@uhasselt.be, an.caris@uhasselt.be, Dries.Meers@vub.ac.be, Cathy.Macharis@vub.ac.be

Abstract. In order to improve the competitive position and efficiency level of multimodal transport, consolidation of freight flows is often suggested. Bundling networks require cooperation between multiple partners in the multimodal transport chain. In this context, the question rises how benefits may be allocated fairly among the spatially distributed participants in the cooperation. A great deal of scientific literature reports on the behavior of allocation methods in collaborations between shippers or carriers making use of unimodal road transport. However, research on cost or savings allocation methods in multimodal transport is scarce. The main contribution of this paper is thus to provide a first insight in the complexity of sharing cost savings fairly amongst shippers who bundle freight flows in order to reach economies of scale in multimodal barge transport. By applying four different allocation methods to two realistic case studies, a comparison is made between simple and straightforward allocation mechanisms and more advanced techniques based on cooperative game theory. Special attention is paid to the savings division amongst coalition partners and collaborative stability. Results demonstrate the influence of cooperation characteristics on allocation outcomes and underline the value of carefully selecting appropriate allocation mechanisms when long-term stability of the multimodal barge collaboration is aspired.

Keywords: Cost allocation; Consolidation; Multimodal barge transportation; Shipper collaboration

1. Introduction

Policy makers at European as well as regional levels express the need to stimulate multimodal transport chains (European Commission, 2011). A growing market share for multimodal transport should mean a shift towards more environmental friendly transport modes, less congestion and a better accessibility of seaports. In order to improve the competitive position and efficiency level of multimodal transport, consolidation of freight flows with differing origin and destination is often suggested as it creates denser freight flows and leads to economies of scale. As freight flows have become smaller and more frequent due to flexibilization, globalization and changing production principles, bundling is needed for inland waterway transport to stay competitive (Hesse and Rodrigue, 2004).

Improving the efficiency of the hinterland by means of complex freight bundling networks contributes to the competitiveness of multimodal transport. In addition, these networks improve the hinterland access of ports. In regions with an extensive waterway network, such as Western Europe, multimodal barge transport provides a suitable alternative for unimodal road transport (Caris et al., 2011). However, further investments and research are necessary to enhance its modal share, as proven by the European NAIADES (Navigation and Inland Waterway Action and Development in Europe) and NAIADES II action programs (European Commission, 2006; European Commission, 2013). In Belgium, inland navigation plays an important role in the hinterland access of the Port of Antwerp (Notteboom, 2007). Notteboom and Rodrigue (2005) introduce a regionalization phase in port development. In their perspective, ports are considered as nodes in multimodal networks and competition exists between transport chains instead of ports. Moreover, bundling and collaboration is often a prerequisite for multimodal services to be competitive to unimodal road transport (Caris et al., 2014).

This paper further elaborates on how to create long term sustainable multimodal collaborations by means of appropriate cost allocation mechanisms. Bundling freight of multiple shippers offers the opportunity to achieve economies of scale and thus boost the competitiveness of multimodal barge transport. Considering the collaborative logistics classification described in Verdonck et al. (2013), the freight bundling problem studied in this paper belongs to the "capacity sharing" category. Shippers jointly use available barges and in this way share vessel capacity. Questions rise as to which type of bundling network is manageable and how benefits may be allocated among the participants in the cooperation. While economies of scale are an obvious advantage for the consolidation of freight flows as a whole (as opposed to the sum of the stand-alone costs of the partners), the benefits for a single partner are not always clear. Caris et al. (2014) indicate that research into which business models are appropriate for this complex cooperation environment can support the integration of inland navigation in the multimodal supply chain. Although research on the analysis of bundling networks is extensive, research on business models in this context is rather scarce. Moreover, literature on business models in multimodal transport is scarce and mainly deals with rail transport operations and the roles that different actors can perform along the supply chain (Lehtinen and Bask, 2012; Flóden and Sorkina, 2014). As a number of actors can be involved in the organization of multimodal transport, also the business model analysis can be centered on these different actors, such as shippers (Flodén and Sorkina, 2014), transport operators (Flodén and Woxenius, 2017), port authorities, terminal operators and shipping lines (van den Berg, 2015). In a market study, Panteia/NEA et al. (2013) identify five multimodal barge transport business models, with differing initiators: a barge operator, a shipping line, a port terminal, a neutral orchestrator and the combination of an inland terminal operator with shipper(s). The business model in place clearly determines the actors' bargaining power and whether and how gains of cargo bundling can be divided among shippers.

Cruijssen et al. (2007) suggest incentive alignment as a crucial facilitator for horizontal cooperation in transport and logistics. Realigning the benefits and burdens among the partners results in an individual responsibility for the attainment of overall coalition profitability. One such realignment mechanism is the fair division of cooperation related costs or savings in such a manner that partners are induced to behave according to the collaborative goal. A great deal of scientific literature reports on the behavior of cost or savings allocation methods in collaborations between shippers or carriers making use of unimodal road transport. A structured overview of allocation mechanisms applied in a unimodal road collaboration context can be found in Verdonck et al. (2016). In multimodal barge transport various types of vessels with differing price structures may be considered for the bundling network. Moreover, the magnitude of the economies of scale resulting from consolidation in barge transport significantly exceeds that of the results obtained in road transport. As such, applying the allocation methods which have been thoroughly studied in a unimodal road context is not so straightforward in a multimodal environment. Different from the unimodal setting, coalition size needs to be synchronized with the used vessel size, and vice versa, in order to ensure coalition profitability and allocation stability. In addition, the geographical location of barge terminals and origin-destination locations may have an impact on cost allocation outcomes. While increasing the geographical coverage of the coalition improves collaborative efficiency in a unimodal setting (Verdonck, 2017), increased pre- and end-haulage reduces the level of collaborative savings in a multimodal context. Collaborating with partners that share the same barge trajectory is more beneficial than collaborating with partners that share only a part of the barge trajectory. Furthermore, partners that show flexibility and contribute more to the collaborative goal, e.g. by performing a part of the barge trajectory alone (if partners share only a part of the barge trajectory) or by changing their shipment frequency, should be rewarded in the allocation of cost savings. Due to these geographical characteristics, questions may raise about the fairness of the applied allocation mechanism and could lead to the implementation of allocation techniques rewarding shipper flexibility. In addition, research on cost or savings allocation methods in multimodal transport is scarce. To the best of our knowledge, the only scientific contributions which study allocation mechanisms in multimodal transport are Soons (2011) and Theys et al. (2008). Both papers apply game theoretic methods to allocate costs fairly in a cooperative multimodal project consisting of terminal operating companies bundling freight. No comparative studies have been performed yet on allocation methods applied in the context of collaboration between shippers making use of multimodal barge transport. In Ramaekers et al. (2016) a first insight is provided in the complexity of sharing cost savings fairly amongst shippers who bundle freight flows in order to reach economies of scale in multimodal barge transport. In this paper, the work of Ramaekers et al. (2016) is significantly elaborated as more cost allocation techniques are tested and an additional case study environment is analyzed. More attention is also given to the stability of the found solutions and recommendations are formulated for shippers who want to bundle freight flows.

This paper adds value to the rather limited research efforts on business models in a multimodal barge context. The main contributions of the paper are the following. First, since game theoretic allocation mechanisms may raise questions from partnering companies about mathematical complexity and fairness transparency, three additional allocation techniques are applied to the multimodal freight bundling problem. Second, special attention is paid to the savings division amongst the coalition partners and the stability of the allocation solutions obtained. Finally, all allocation and stability analyses are performed within the context of two case studies. In this way, recommendations could be formulated to shippers considering multimodal freight bundling on how they should tackle the allocation challenge considering the characteristics of the cooperation and its partners. The first case study is carried out within the Aggregate-Disaggregate-Aggregate (ADA) framework (Maes et al., 2011) and uses real data from a freight transport model for Flanders. Since the ADA assumptions may not always be realistic and could prevent shippers from optimally bundling their freight flows, a second case study, situated in the hinterland of the Port of Antwerp, is studied.

The remainder of this paper is organized as follows. In Sect. 2, relevant literature on multimodal freight bundling is discussed. Then, the current research field of allocation methods proposed for collaborations in unimodal transport is summarized and detailed information is provided on the applied allocation techniques in Sect. 3. Next, Sect. 4 presents two case studies in which shippers cooperate to bundle their freight flows and make use of multimodal barge transport. Based on these case studies, Sect. 5 discusses the numerical comparison between simple and straightforward allocation methods and more advanced techniques based on cooperative game theory. Finally, conclusions and recommendations are formulated.

2. Geographical perspective on multimodal freight bundling

Multiple research efforts have been undertaken to investigate bundling networks in multimodal transport. The basic idea is to consolidate loads for efficient long-haul transportation (e.g. by rail, inland waterway barge or ocean-going vessel), while taking advantage of the efficiency of local pickup and delivery operations by truck (Bektas and Crainic, 2008). Kreutzberger (2010) analyzes in which transport landscape which bundling network types ensure the lowest operational cost and which of the lowest cost bundling networks may be competitive with unimodal road transport. Kreutzberger and Konings (2013) propose a new concept to bundle the container hinterland transport flows of the seaports of Rotterdam and Antwerp in order to increase the size of trainloads, the service frequency or the network connectivity and hence to improve the cost performance and quality of rail hinterland transport. The total transport cost depends to a large extent on the location of the senders and receivers, the transport and terminal network. In practice, multimodal solutions with both pre- and end-haulage by truck might not be able to compete with direct road transport on short distances, given the longer break-even distance (Kim and Van Wee, 2011). As such, bundling and collaboration could be considered a prerequisite for multimodal services to be competitive to unimodal road transport

Bundling networks in multimodal barge transport, which are the focus of our paper, have been studied amongst others by Caris et al. (2011), Caris et al. (2012) and Konings et al. (2013). Woxenius (2007) discusses the most important network designs that fit the multimodal context. The network type that is most suitable for a specific geographic context depends on factors such as the available infrastructure network and the spatial distribution of the shippers and volumes that are willing to bundle their goods in a multimodal transport service. Caris et al. (2011) suggest that there exist two options for freight bundling in multimodal barge transport. Freight may be consolidated in the hinterland network or could be bundled in the port area. Our paper focuses on the first alternative considering shippers who offer bundled freight flows to terminals and in this way improve multimodal efficiency and achieve economies of scale. As Trip and Bontekoning (2002) describe, this bundling of relatively small flows requires bundling networks that are more complex than those for conventional point-to-point bundling. Using complex bundling via intermediate nodes, load factors of barges may be increased and transport frequency could be improved. However, complex bundling networks also require complex node operations and thus depend on the quality of the terminals involved in the network. Braekers et al. (2013) present a decision support tool for bundling freight in a corridor network in multimodal barge transport. Barge operators, logistic service providers or shipping lines that want to offer regular roundtrip barge services between a number of ports located along the same waterway may use this model to determine vessel capacity and frequency of these roundtrips. Van Lier et al. (2016) discuss bundling of freight activities at the operational level. Shippers attain scale economies and a better utilization of transport equipment through consolidation of freight inside a loading unit. The cost of freight transport may be decreased by raising the fill rate of loading units. This may on the one hand reduce the costs of pre- and end-haulage by road or on the other hand increase the attractiveness of multimodal freight transport for further continental distribution.

Considering the business models of Panteia/NEA et al. (2013), the focus of this paper is on multimodal freight bundling in barge transport initiated by collaborating shippers possibly in combination with a neutral orchestrator. Not only contributes this type of horizontal collaboration to the competitiveness of multimodal transport, it could also add value to the development of recent trends in freight transport like the synchromodality concept. The distinctive characteristic of synchromodality is the horizontal integration of the whole transport system balancing the transport service of different modalities. In this way, a service can be provided that is no longer dependent on the type of modality that is used. The main value of synchromodality lies in the increased alignment of supply to demand, based on dynamic information about customer preferences and expected transport service performance (Tavasszy et al., 2015). To achieve synchromodality in practice, appropriate revenue management models should be developed (Van Riessen et al., 2015), including multimodal cost allocation mechanisms.

3. Collaborative cost allocation

As the goal of a logistics cooperation is to increase the participants' efficiency and since collaboration often results in additional profits or cost savings, a great deal of scientific literature on unimodal collaborative logistics devotes its research attention to the identification of efficient allocation schemes. Dividing the coalition costs or savings 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. In Sect. 3.1 the current research field of collaborative cost allocation is summarized. The allocation methods that are applied to the numerical experiments of Sect. 4 are explained in detail in Sect. 3.2.

3.1 Cost allocation mechanisms: state-of-the-art

Verdonck et al. (2016) provide a structured review of allocation mechanisms applied in unimodal horizontal collaborations distinguishing between (1) proportional sharing mechanisms, (2) allocation mechanisms using game theory concepts and (3) allocation techniques designed to cope with additional cooperation properties.

Firstly, the most commonly used profit or cost division mechanism in practice is the proportional allocation method (Liu et al., 2010). In this case, the collaborative profit is allocated to the cooperating organizations equally, on the basis of, among others, their individual cost level or the volume they have to transport as a consequence of their engagement in the cooperation (Verdonck et al., 2016).

Secondly, a logistics cooperation clearly matches the structure of a cooperative game. Collaborating partners share and consolidate freight and receive or make payments in return. This cooperation process results in an allocation of benefits or costs to each participant that may be considered equivalent to the outcome of a cooperative game. The grand coalition N coincides with all participating shippers i in the cooperation, while a coalition S denotes a subset of collaborators. When a coalition S collaborates, they realize 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 $v(S)$, are equivalently calculated as $\sum_{i \in S} c(\{i\}) - c(S)$. Each considered allocation method assigns a cost amount y_i to coalition participant i. The cost allocation game studied in this paper also shows clear similarities with the "bus game" described in Fragnelli et al. (2004) in the sense that partners share the cost of the vessels (cf. buses) they jointly use to serve customer demand. A relevant concept in the context of logistics cooperation is the notion of the core of a cooperative game (Shapley, 1952). The core of a game consists of all allocations that are budget balanced (efficient) and guarantee that no single participant or coalition of participants benefits from leaving the cooperation (stability). A drawback of this solution concept is the fact that the core of a cooperative game may be empty. A well-known allocation method based on the foundations of game theory is the Shapley (1953) value. 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 (Verdonck et al., 2016). A more complex allocation mechanism supported by game theory is the nucleolus. This profit or cost sharing procedure, developed by Schmeidler (1969), has the distinct property of minimizing the maximal excess, which constitutes the difference between the total cost of a coalition and the sum of the costs allocated to its participants.

Finally, several authors have developed distinct, more intuitively clear allocation mechanisms that account for certain specific cooperation characteristics, some of them partly based on game theory ideas (Verdonck et al., 2016). Tijs and Driessen (1986) discuss three allocation techniques based on the division of the total collaborative costs in separable and non-separable costs. Frisk et al. (2010) create profit sharing mechanisms with the goal of finding a stable allocation that minimizes the largest relative difference in cost savings between any pair of cooperating partners. A detailed description of their Equal Profit Method (EPM) can be found in Sect. 3.2. Özener and Ergun (2008) develop allocation mechanisms ensuring that, among others, existing partners do not loose savings when an additional company joins the collaboration. Xu et al. (2013) create allocation mechanisms accounting for the coordination costs (e.g. ICT investments) that are associated with the set-up of a horizontal logistics collaboration. Hezarkhani et al. (2016) describe a gain sharing method accounting for the highly competitive nature of the freight transport market. The authors introduce a competitiveness property which guarantees that allocations preserve the competitive positions of cooperation participants.

The overview provided in the previous paragraphs demonstrates that a wide range of possible allocation mechanisms exists. As each method has its specific benefits and drawbacks, it remains ambiguous which technique(s) could guarantee stability and sustainability in a multimodal freight bundling context. The only scientific contributions which study allocation mechanisms in multimodal transport are Soons (2011) and Theys et al. (2008) applying game theoretic methods to allocate costs fairly in a cooperative multimodal project consisting of terminal operating companies bundling freight. Moreover, applying the allocation methods which have been thoroughly studied in a unimodal road context is not so straightforward in a multimodal environment. Different from the unimodal setting, available vessel sizes and geographical characteristics of the multimodal setting need to be taken into account in order to ensure coalition profitability and allocation stability. To avoid an increase in allocated costs, the number of partners in the coalition needs to be synchronized with the vessel size. Furthermore, the geographical location of collaborating partners can influence the magnitude of the cost savings. For example, increased pre- and end-haulage reduces the level of collaborative savings while collaborating with partners that share the same barge trajectory increases the level of collaborative savings. Besides ensuring coalition profitability and allocation stability, allocation methods also need to reward the contribution of partners to the collaborative goal. For these reasons, in Sect. 5 four different allocation mechanisms are applied to divide logistics costs after bundling within the context of two case studies. A comparison is made between two simple and straightforward cost allocation methods often used in practice and two more advanced techniques based on cooperative game theory. In addition, special attention is paid to the stability of the found solutions. In this way, we are the first to provide insight in the complexity of sharing cost savings fairly amongst shippers who bundle freight flows in order to reach economies of scale in multimodal barge transport.

3.2 Applied cost allocation methods: description, calculation and properties

This section provides details on the theoretical foundation, calculation approach and fairness properties of the four allocation mechanisms compared for their efficacy in Sect. 5.

The reasons for choosing the proportional, decomposition, Shapley and Equal Profit method are the following. Up to now only game theoretic methods have been applied to allocate costs fairly in a cooperative multimodal network (Soons, 2011; Theys et al., 2008). The most prevalent solution concepts within cooperative game theory are the Shapley value and the nucleolus. The preference for the Shapley value may be explained by its ease of calculation. However, basic game theoretic mechanisms may raise questions about mathematical complexity, applicability, fairness transparency and stability in practice. As such, the importance of convenient implementation and interpretation in practice favors the use of the proportional and decomposition methods. Moreover, a drawback of using the Shapley value is that, although it guarantees a unique and efficient solution, in case of a non-empty core, Shapley allocations may not lie in the core of the game and thus do not satisfy stability. By incorporating stability constraints, EPM allocations guarantee that no subgroup of partner companies has the incentive to leave the grand coalition and be better off acting alone. In addition, each of the applied allocation mechanisms leads to a one-point solution. Consequently, coalition partners do not have to negotiate on the choice of actual payoff as each of the techniques generates a unique solution.

Cost allocations satisfy a variety of properties desirable in the context of a logistics collaboration. Table 1, based on Vanovermeire (2014) and Verdonck et al. (2016), provides an outline of allocation characteristics satisfied by the Shapley value, the EPM and the applied proportional mechanisms.

Table 1. Fairness properties satisfied by proportional, decomposition, Shapley and EPM allocations

Property	Proportional allocation	Decomposition method	Shapley	EPM
Group rationality (efficiency)[1]	✓	✓	✓	✓
Individual rationality[2]			✓	✓
Anonymity (symmetry)[3]			✓	✓
Stability[4]				✓
Dummy[5]			✓	
Additivity[6]			✓	

[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 organizations: $c(S \cup \{i\}) = c(S \cup \{j\}) \rightarrow y_i = y_j, \forall\, S \subset N$

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

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

Proportional allocation based on volume 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 organizations equally, on the basis of their 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 as 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; Verdonck et al., 2016).

The proportional allocations computed in our case study are volume based. This volume is expressed as the number of shipments z_i per year that each coalition partner i requires along the same trajectory. Total collaborative savings are weighted with each participant's volume as follows:

$$y_i = w_i \cdot v(N) \qquad \forall i \in N \tag{1}$$

with $w_i = \frac{z_i}{\sum_{i \in N} z_i}$.

Decomposition Method A second gain sharing mechanism especially suited for multimodal freight transport is based on a decomposition of the total trajectory in common links of the participants. A volume based proportional allocation, as described in the previous paragraph, is then applied on each of these links separately. For example, in a cooperation between three shippers A, B and C, the total transport chain may be divided in two common links. On the first common link shippers A and B bundle their freight. On the second link, the freight of all three participants is consolidated. The proportional allocation method will share collaborative savings on the first link between shippers A and B according to their number of shipments. Along the second link, coalition savings will be shared proportionally according to the number of shipments of participants A, B and C respectively.

Shapley Value To allow a comparison of relatively simple and intuitive proportional methods with more complex game theoretic allocation methods, we chose Shapley as our third allocation mechanism. The Shapley value (1953) 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:

$$y_i = \sum_{S \subset N:\, i \in S} \frac{(|S|-1)!(|N|-|S|)!}{|N|!} \left[c(S) - c(S \setminus \{i\})\right] \tag{2}$$

with $|.|$ denoting the number of participants in the considered (sub)coalition. The Shapley value provides a unique allocation with characteristics that are beneficial in the context of a logistics cooperation, as visualized in Table 1. However, the Shapley value has an important disadvantage, namely that this allocation may not lead to a stable collaboration (Frisk et al., 2010; Liu et al., 2010; Verdonck et al., 2016).

Equal Profit Method 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 organizations are as similar as possible. For this purpose, Frisk et al. (2010) develop the EPM. This allocation technique has the goal of finding a stable allocation that minimizes the largest relative difference in cost savings between any pair of cooperating partners. In order to find the EPM allocations to all participants, the following linear program needs to be solved to optimality:

$$Min\ f \tag{3}$$

Subject to

$$f \geq \frac{y_i}{c(\{i\})} - \frac{y_j}{c(\{j\})} \qquad \forall\, i, j \in N \tag{4}$$

$$\sum_{j \in S} y_j \leq c(S) \qquad \forall\, S \subseteq N \tag{5}$$

$$\sum_{j \in N} y_j = c(N) \tag{6}$$

The first constraint set (4) measures the pairwise difference between the relative savings of the participants. The objective function (3) minimizes the largest difference using variable *f*. Constraint sets (5) and (6) ensure that the allocation is stable. As such, the cost allocation guarantees that no subcoalition S exists in which a set of partners would be better off (5) and the total collaborative cost is shared as the grand coalition forms (6) (Verdonck et al., 2016).

4. Case studies

To demonstrate the use of cost allocation methods in a multimodal barge context, two case studies are introduced in this section. The first case study is carried out within the framework of the ADA model of Ben-Akiva and de Jong (2013) and analyzes the cost allocation problem with the use of real data. The ADA model is originally developed for the Netherlands but the concepts have also been applied to Flanders (Maes et al., 2011). Because this first case study is implemented in the ADA framework, the ADA assumptions are taken into account. However, these assumptions may not always be realistic and could prevent shippers from optimally bundling their freight flows. Therefore, a second case study is presented in which the assumptions of the ADA model are relaxed. In the second case study, barge freight is bundled in the hinterland of the Port of Antwerp. In Sect. 4.1 the ADA-based case study is described. In Sect. 4.2 the case study in the hinterland of the Port of Antwerp is discussed. In practice, multimodal solutions with both pre- and end-haulage by truck cannot compete with direct road transport on short distances, given the longer break-even distance (Kim and Van Wee, 2011). The concentration of a large demand close to the port of Antwerp and other favourable conditions such as the large amount of terminals in its direct hinterland, however make that multimodal services to and from the port, as depicted in the second case study, can be cost-competitive on rather short distances (Meers et al., 2014).

We acknowledge the limitations of our experimental study. The consideration of a distinct multimodal transport business model (cf. Panteia/NEA et al., 2013) and the use of specific case study data (e.g. cost rates, vessel types, terminal locations, shipper locations) could influence the general validity of our findings. Our conclusions, however, show the influence of cooperation characteristics on allocation results and underline the value of carefully selecting allocation mechanisms when long-term stability of the multimodal barge collaboration is aspired.

4.1 ADA-based case study

The ADA model is an activity-based freight transport model developed by Ben-Akiva and de Jong (2013) for the Netherlands. Freight transport models are used on an international, national or regional level to forecast transport demand, to test transport policy measures and to predict the impacts of new infrastructure on traffic. In contrast to traditional transport models which handle all steps at the aggregate level, the ADA model uses disaggregate data to model logistics elements such as the choice of shipment size and transport chain including mode choice. For reasons of data availability, the other elements of the freight transport model, besides the logistics module, are specified at an aggregate level. These other elements are the production-consumption (PC) matrices that provide flows of goods by commodity type between two zones (e.g. municipalities) and the assignment of freight flows to the network. The PC matrices could be generated by spatial input-output models or spatial computable general equilibrium models. The PC flows serve as input for the logistics module, after disaggregation of the zone-to-zone flows to the level of firm-to-firm (sender-to-receiver) flows. The outputs of the logistics module consist of origin destination (OD) vehicle flows, which are used in aggregate network assignment (De Jong and Ben-Akiva, 2007).

In the freight transport model for Flanders, based on the ADA model, the 308 municipalities of Flanders are used as zones. The model starts from the PC flows per NSTR category between the different zones. The NSTR classification is a standard goods classification for transport statistics, which is often used in Europe. In a first step, the disaggregation step, the PC flows are disaggregated to firm-to-firm flows, based on the number of producers of the commodity in the first zone, the number of consumers of the commodity in the second zone and the fraction of actually realized links between senders and receivers of the two zones. Next, all possible transport chains for every firm-to-firm flow are built and the Total Logistics Cost (TLC) is calculated for each transport chain. An average shipment size (based on the NSTR category) is used to build the transport chains. The TLC function exists of an ordering cost, an inventory cost, a capital cost of the goods in transport and in inventory and a transport cost. The transport cost is split into several components: a variable cost based on the distance of the links traveled and a loading and unloading cost for the different transport modes. The TLC is used to determine the optimal transfer points for chains which use several transport modes and to determine the best transport chain(s) for a given firm-to-firm flow.

The notation, data and formulas necessary for the TLC calculations of the numerical experiments discussed in Sect. 5.1 are provided in Table 2 and Table 3.

Table 2. Notation and data

Symbol	Description	Value
o	Order cost	55€
Q	Yearly demand (in ton)	*Case specific*
q	Shipment size (in ton)	68.4 (273.6)
D_{ph}	Distance pre haulage	*Case specific*
D_{mh}	Distance main haulage	*Case specific*
D_{eh}	Distance end haulage	*Case specific*
TC_r	Transport cost road	1€/km
TC_{iww}	Transport cost inland waterways	6 (9)€/km
TT	Total transport time	*Case specific*
Cap_r	Capacity truck	27 tons
MNT	Minimum number of trucks	*Case specific*
Cap_{iww}	Capacity vessel	1000 (2000) tons
$UsedCap_{iww}$	Vessel fill rate	*Case specific*
L_r	Cost to (un)load truck	2€/ton
L_{iww}	Cost to (un)load vessel	0.4€/ton
d	Interest rate (per year)	4%
v	Value of goods	672€/ton
w	Warehouse cost	20%

Using the data above, the TLC is calculated as follows. Based on the fixed shipment size, first the number of shipments per year z is calculated and rounded up to the next integer number. Next, the order cost, the transport cost, the capital cost of goods in transit, the inventory cost and the capital cost of inventory are calculated, using the formulas defined in Table 3 (Maes et al., 2011).

Table 3. TLC formulas

Cost component	**Formula**
Order cost	$o * z$
Transport cost	$[D_{ph}*TC_r*MNT+D_{mh*}TC_{iww}*(q/UsedCap_{iww})+D_{eh}*TC_r*MNT+ q*(4*L_r + 2*L_{iww})]*z$
Capital cost of goods in transit	$(TT * d * v * Q)/(365 * 24)$
Inventory cost	$\frac{q}{2} * w * v$
Capital cost of inventory	$\frac{q}{2} * d * v$

With *MNT* representing the minimum number of trucks needed for the pre- and end-haulage, which is calculated as q/Cap_r and rounded to the next integer number, $UsedCap_{iww}$ representing the vessel fill rate and *TT* representing the Total Transport time, which is calculated as the sum of the travel time (road and inland waterways transport) and the waiting time for a truck or vessel to be available. For detailed calculations on all cost components, the reader is referred to Maes et al. (2011).

In this case study, all 'road - inland waterways - road' transport chains of the transport model are considered and the options for bundling are studied. The stand-alone cost is defined as the TLC for a specific partner when no bundling is performed. At this point, the barge capacity is not fully used and thus economies of scale can be achieved when bundling with other partners on the same barge trajectory. The firm-to-firm flows are then bundled for flows which have at least one terminal in common and the TLC of the bundled situation is calculated. Next, collaborative savings are determined as the difference between the TLC of the bundled situation and the sum of the stand-alone costs of the partnering shippers. Finally, the collaborative savings are shared among the participants of the coalition using the four methods described in Sect. 3.2. In the next paragraphs, an example is given of how the sharing of the collaborative savings is determined for the four different allocation methods.

Example: collaborative gain sharing among partners In this example, firm-to-firm flows which use the same end terminal for their barge transport are bundled. Three flows are used: Aalst-Antwerp (partner A), Zaventem-Antwerp (partner B) and Mechelen-Antwerp (partner C). The barge trajectory (Figure 1) that is followed is Brussels-Vilvoorde-Willebroek-Deurne. These terminals are determined based on a minimization of the TLC. The goods from Aalst start their barge transport in Brussels, the goods from Zaventem start their barge transport in Vilvoorde and the goods from Mechelen start their barge transport in Willebroek. All goods are unloaded from the vessel in Deurne. The number of shipments per year and the stand-alone cost for each partner are given in Table 4. The stand-alone cost is calculated as the annual TLC each partner incurs when performing the multimodal trajectory on an individual basis for all its shipments. The number of shipments per year is calculated in the ADA-model based on the optimal shipment size, which is given for every NSTR-category. Based on the ADA assumptions, the number of shipments cannot be changed when partners bundle their goods and thus, if one partner has three shipments per year and another partner has seven shipments per year, only three shipments can be bundled and the second partner still has to transport four shipments alone.

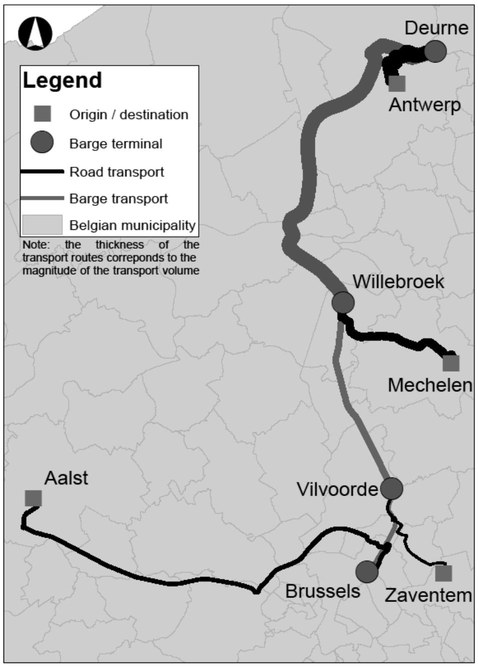

Figure 1. Multimodal trajectory of ADA-based case study

Table 4. Example: Situation before bundling

Firm-to-firm flow	Number of shipments	Stand-alone TLC (in €)
Aalst-Antwerp	7	13112
Zaventem-Antwerp	3	8461
Mechelen-Antwerp	17	20792

The barge trajectory (Figure 1) can be divided in three parts for this example: Brussels-Vilvoorde, Vilvoorde-Willebroek and Willebroek-Deurne. The first part, Brussels-Vilvoorde, is only used by the flow Aalst-Antwerp and no bundling can take place on that part. The second part, Vilvoorde-Willebroek, is used by two partners: three shipments can be bundled for this part of the trajectory, the four residual shipments of Aalst-Antwerp cannot be bundled. The third part, Willebroek-Deurne, is used by all three partners: three shipments can be bundled for the three partners, an additional four shipments can be bundled for two partners (Aalst-Antwerp and Mechelen-Antwerp) and ten shipments of Mechelen-Antwerp cannot be bundled. The total logistic cost for this situation equals 40311€ and the total gain is 2055€.

Using the proportional allocation method, the total savings amount is divided over the partners based on the number of shipments of each partner. This results in a relative cost saving of 4.06% for partner A, 2.70% for partner B and 6.22% for partner C. With the decomposition method, the cost savings amount is calculated for each part of the barge trajectory separately. In this example, the barge trajectory can be divided in three parts: Brussels-Vilvoorde, Vilvoorde-Willebroek and Willebroek-Deurne. The first part, Brussels-Vilvoorde, is only used by the flow Aalst-Antwerp so no bundling can take place on this part. In the second part, Vilvoorde-Willebroek, two participants can bundle freight. The benefit of 278€ is allocated to these two partners based on their number of shipments. In the last part of the trajectory, Willebroek-Deurne, the shipments of the three partners can be bundled. The benefit of 1777€ earned on this part of the trajectory is again divided over the three partners based on their respective number of shipments. In this way, the decomposition method results in savings percentages of 5.00%, 3.32% and 5.38% for partners A, B and C respectively. To determine the Shapley value for each partner, equation (2) is used. In this way, each participant is allocated the weighted average of his contributions to all possible (sub)coalitions. Shapley based relative savings are 6.48% for partner A, 5.84% for partner B and 3.42% for partner C. The EPM allocations are calculated using linear program (3) – (6). Besides their guaranteed stability, these allocations minimize the pair wise difference between the relative transport cost savings of the participants, being 8.44% for A, B and C. The results of applying the four cost allocation methods to the example are shown in Table 5.

Table 5. Example: Cost allocation results (in €)

Firm-to-firm flow	Stand-alone	Proportional	Decomposition	Shapley	EPM
Aalst-Antwerp	13112	12580	12457	12263	12504
Zaventem-Antwerp	8461	8233	8180	7967	8224
Mechelen-Antwerp	20792	19498	19673	20081	19583

4.2 Case study in the hinterland of the Port of Antwerp

The assumptions of the ADA-based case study may not always be realistic and could prevent shippers from optimally bundling their freight flows. Therefore, a second case study is developed in which the assumptions of the ADA model are relaxed. As opposed to the first case study, shipment sizes of partnering shippers are not fixed in this second experiment. Partners are able to align their shipment frequencies z_i to increase the number of bundling opportunities and in this way improve collaborative synergy. Moreover, consequential to bundling freight, shippers aim to improve customer service by means of higher delivery frequencies.

In this second case study, barge freight is bundled in the hinterland of the Port of Antwerp. Firm-to-port flows that are studied are Aalst-Antwerp, Zaventem-Antwerp and Mechelen-Antwerp. The barge trajectory under consideration is Brussels-Vilvoorde-Willebroek-Antwerp (Figure 2). Since freight flows are now destined to the Port of Antwerp, end-haulage via road is avoided.

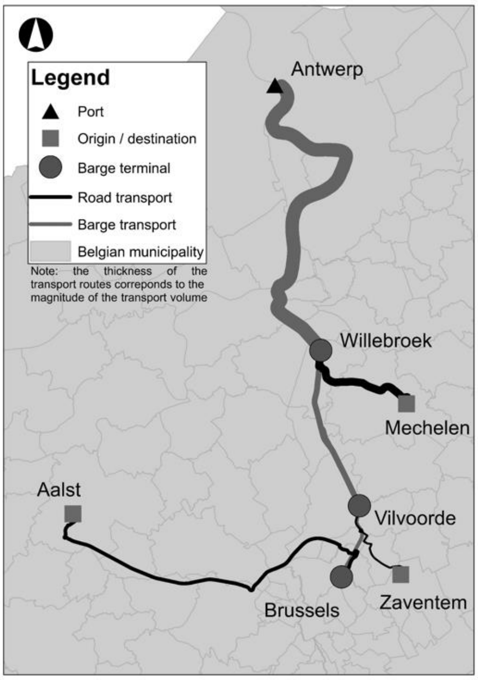

Figure 2. Multimodal trajectory of case study in the hinterland of the Port of Antwerp

The data necessary for the TLC calculations of the numerical experiments discussed in Sect. 5.2 are provided in Table 6. The TLC formulas are equivalent to those listed in Table 3. Because of the hinterland setting, demand volumes are expressed in TEU (Twenty foot Equivalent Units), available vessel types have capacity levels of 96 and 165 TEU and cost levels are adapted accordingly.

Table 6. Notation and data

Symbol	Description	Value
o	Order cost	5.5€
Q	Yearly demand (in TEU)	*Case specific*
q	Shipment size (in TEU)	Q/z_i
D_{ph}	Distance pre haulage	*Case specific*
D_{mh}	Distance main haulage	*Case specific*
TC_r	Transport cost road	1€/km
TC_{iww}	Transport cost inland waterways	6 (9)€/km
TT	Total transport time	*Case specific*
Cap_r	Capacity truck	2 TEU
MNT	Minimum number of trucks	*Case specific*
Cap_{iww}	Capacity vessel	96 (165) TEU
$UsedCap_{iww}$	Vessel fill rate	*Case specific*
L_r	Cost to (un)load truck	15€/TEU
L_{iww}	Cost to (un)load vessel	30€/TEU
d	Interest rate (per year)	4%
v	Value of goods	33.6€/TEU
w	Warehouse cost	20%

5. Allocation results

In this paper, a first insight is provided in the complexity of sharing collaborative cost savings fairly amongst shippers who bundle freight flows in order to reach economies of scale in multimodal barge transport. The impact of the number of partners, the equality of partners, the shipment size and shipment frequency on allocation values and coalition stability is examined. In Sect. 5.1 allocation and stability results are discussed for the ADA-based case study. Sect. 5.2 analyzes the results for the case study setting in the hinterland of the Port of Antwerp.

5.1 ADA-based case study

In this case study, the impact of the number of partners, the equality of partners and the shipment size is examined. The situation of three, four and five partners is investigated, both for partners with an equal and an unequal amount of shipments. Two shipment sizes are examined: 68.4 tons and 273.6 tons. For each scenario the case of a common end terminal (Figure 1) is studied. The case of a common start terminal leads to analogue results and the case of a common barge trajectory (both terminals in common) is a special case of the one that is studied.

It is assumed that two vessel types are available: a vessel with a capacity of 1000 tons and a cost of 6€/km and a vessel with a capacity of 2000 tons and a cost of 9€/km. The smallest vessel is used first, only if the bundled freight exceeds its capacity, the larger vessel is utilized. When the small vessel can be used for the bundled freight, bundling always leads to a higher fill rate and therefore, to a lower transport cost. In this case, important properties of cost allocation methods as individual rationality and stability are always satisfied. If the larger vessel needs to be used, adding more realistic characteristics of multimodal barge transport to the problem, attention needs to be paid to the properties of the allocation methods applied.

The results of the experiments with shipment size 68.4 tons are summarized in Tables 7 and 8. Analogue to the example described in Sect. 4.1, first the stand-alone cost (the cost without bundling) is given. Next, the results after bundling are provided for each partner using the proportional allocation method, the decomposition method, the Shapley value and the EPM.

Table 7. Results: equal shipment volume, shipment size 68.4 tons (in €)

	Firm-to-firm flow	Stand-alone	Proportional	Decomposition	Shapley	EPM
3 partners	Aalst-Antwerp	13112	12067	11959	11959	11963
	Zaventem-Antwerp	12466	11420	11312	11312	11419
	Mechelen-Antwerp	11792	10747	10963	10963	10852
4 partners	Aalst-Antwerp	13112	11855	11747	11747	11730
	Zaventem-Antwerp	12466	11208	11100	11100	11207
	Zaventem-Antwerp	12466	11208	11100	11100	11207
	Mechelen-Antwerp	11792	10535	10859	10859	10662
5 partners	Aalst-Antwerp	13112	11858	11685	11685	11704
	Zaventem-Antwerp	12466	11211	11038	11038	11184
	Zaventem-Antwerp	12466	11211	11038	11038	11184
	Mechelen-Antwerp	11792	10538	10797	10797	10641
	Mechelen-Antwerp	11792	10538	10797	10797	10641

Table 8. Results: unequal shipment volume, shipment size 68.4 tons (in €)

	Firm-to-firm flow	Shipments	Stand-alone	Proportional	Decomposition	Shapley	EPM
3 partners	Aalst-Antwerp	7	13112	12580	12457	12263	12504
	Zaventem-Antwerp	3	8461	8233	8180	7967	8224
	Mechelen-Antwerp	17	20792	19498	19673	20081	19583
4 partners	Aalst-Antwerp	7	13112	12276	12114	11868	12056
	Zaventem-Antwerp	3	8461	8102	8033	7876	8049
	Zaventem-Antwerp	9	14484	13408	13200	13062	13248
	Mechelen-Antwerp	17	20792	18760	19198	19741	19193
5 partners	Aalst-Antwerp	7	13112	12226	12043	11812	11970
	Zaventem-Antwerp	3	8461	8081	8003	7849	8015
	Zaventem-Antwerp	9	14484	13344	13108	13005	13146
	Mechelen-Antwerp	17	20792	18639	19024	19685	19193
	Mechelen-Antwerp	5	9988	9355	9468	9295	9321

If the partners are equal in size, the results of the decomposition method are equal to the results of the Shapley value (Table 7). Compared to the proportional allocation method, decomposition and Shapley favor partners that take part in more links of the barge trajectory, i.e. more benefit is granted to Zaventem-Antwerp and Aalst-Antwerp both taking part in two bundled links. In the three partner coalition, for example, Shapley and decomposition allocate a savings percentage of 8.79% to Aalst-Antwerp and 9.26% to Zaventem-Antwerp, compared to savings percentages of 7.97% and 8.39% for the proportional allocation method. If the partners are unequal in size, the four cost allocation methods lead to different results (Table 8). Compared to the proportional allocation method, the decomposition method favors partners that take part in more bundled links. Comparing the results of the Shapley value to those of the decomposition method for three partners, the partners taking part in more bundled parts are even more in favor. However, these participants are coincidentally also the smaller participants in the coalition and Shapley tends to favor smaller coalition participants, as visualized in Figure 3. When an analogue comparison is made for coalitions established between five partners, insights can be improved and it can be concluded that the Shapley value especially favors the smaller partners. For example, the two flows from Zaventem to Antwerp both benefit from the Shapley value compared to the decomposition method but the smaller flow (three shipments, Shapley savings percentage = 7.23%, decomposition savings percentage = 5.41%) is more rewarded by the Shapley value than the larger flow (nine shipments, Shapley savings percentage = 10.21%, decomposition savings percentage = 9.50%). The difference between the Shapley value and the decomposition method is 1.9% for the smaller flow and only 0.8% for the larger flow. When comparing the results for the two flows from Mechelen to Antwerp, the results are even more distinct: although this flow only takes part in one bundled link, the Shapley value leads to favoring results compared to the proportional, decomposition and EPM allocation method for the smaller partner (five shipments). For the larger partner (17 shipments) the Shapley value grants the least relative benefit of all cost allocation methods to this partner. In this case, savings percentages are 10.36%, 8.50%, 5.32% and 7.69% for proportional, decomposition, Shapley and EPM allocations respectively. EPM provides the most equally spread transport cost savings among the partners of the coalition both for equal and unequal partners (Figure 4).

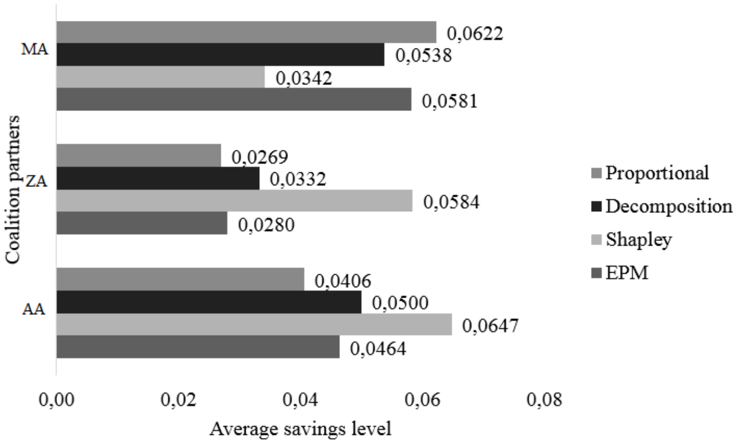

Figure 3. Average savings level (in %) for coalition of three unequal partners, with Shapley favoring the smaller partners Zaventem-Antwerp (ZA) and Aalst-Antwerp (AA)

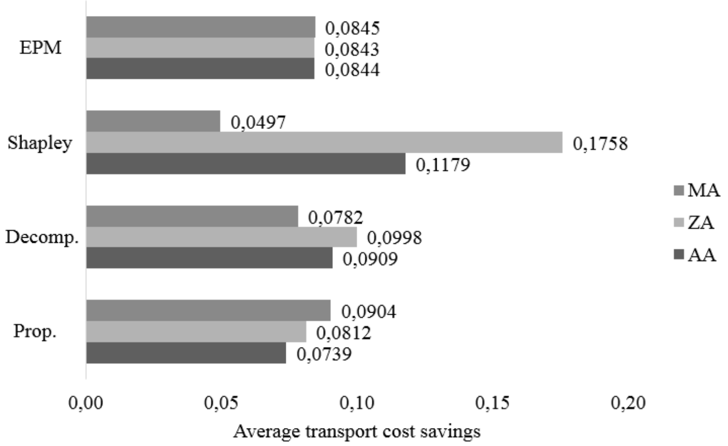

Figure 4. Average transport cost savings (in %) for coalition of three unequal partners, with EPM providing the most equally spread cost savings

For the experiments with the shipment size of 68.4 tons, only the small vessel type is needed to transport the bundled freight and as a consequence, bundling always leads to a lower transport cost since the total cost of the vessel can be divided over more tons. Therefore, important properties of cost allocation methods as individual rationality and a stable cooperation are always satisfied. Although one would intuitively expect that bundling always leads to improvements, this is not always the case in the multimodal context. Large differences in costs for different vessel types make it possible that adding an extra partner to the coalition leads to a worsening situation for all partners and thus an instable solution as not all fairness properties are satisfied. To illustrate the use of the cost allocation methods when more vessel types are used, the same experiments are repeated with a shipment size of 273.6 tons. In this case, four and five partners can only bundle their freight if the larger type of vessel is used since the small vessel has a capacity of only 1000 tons. The results for the experiments with a shipment size of 273.6 tons are summarized in Tables 9 and 10. As explained in more detail further on, stability cannot be guaranteed in this case. Therefore, EPM has been combined with the ε-core concept (Frisk et al., 2010). ε-EPM allocations are indicated in *italic* font in Tables 9 and 10.

Table 9. Results: equal shipment volume, shipment size 273.6 tons (in €)

	Firm-to-firm flow	Stand-alone	Proportional	Decomposition	Shapley	(ε-) EPM
3 partners	Aalst-Antwerp	28467	28168	28137	28137	28150
	Zaventem-Antwerp	28020	27722	27691	27691	27726
	Mechelen-Antwerp	27810	27511	27573	27573	27526
4 partners	Aalst-Antwerp	28467	28186	28195	28155	*28140*
	Zaventem-Antwerp	28020	27740	27706	27709	*27693*
	Zaventem-Antwerp	28020	27740	27706	27709	*27693*
	Mechelen-Antwerp	27810	27529	27588	27622	*27668*
5 partners	Aalst-Antwerp	28467	28171	28169	28130	28088
	Zaventem-Antwerp	28020	27725	27679	27673	27669
	Zaventem-Antwerp	28020	27725	27679	27673	27669
	Mechelen-Antwerp	27810	27514	27561	27586	27611
	Mechelen-Antwerp	27810	27514	27561	27586	27611

Table 10. Results: unequal shipment volume, shipment size 273.6 tons (in €)

	Firm-to-firm flow	Shipments	Stand-alone	Proportional	Decomposition	Shapley	(ε-) EPM
3 partners	Aalst-Antwerp	2	28467	28310	28272	28213	28282
	Zaventem-Antwerp	1	25023	24944	24925	24858	24937
	Mechelen-Antwerp	5	36432	36040	36098	36224	36076
4 partners	Aalst-Antwerp	2	28467	28336	28351	28264	*28262*
	Zaventem-Antwerp	1	25023	24957	24943	24984	*25089*
	Zaventem-Antwerp	3	30983	30788	30744	30691	*30601*
	Mechelen-Antwerp	5	36432	36105	36149	36248	*36235*
5 partners	Aalst-Antwerp	2	28467	28302	28314	28206	*28160*
	Zaventem-Antwerp	1	25023	24940	24924	24931	*24986*
	Zaventem-Antwerp	3	30983	30736	30688	30634	*30591*
	Mechelen-Antwerp	5	36432	36019	36056	36224	*36217*
	Mechelen-Antwerp	2	27772	27607	27622	27609	*27650*

Compared to the results of the experiments with a shipment size of 68.4 tons, two important differences can be observed. First, stability cannot be guaranteed in this case. When the coalition is extended from three to four partners, all partners have a higher allocated cost due to the use of the larger (and more expensive) vessel type and thus a coalition of three partners could be preferred over a coalition of four partners. When the coalition is extended from four to five partners, the extra costs of the larger vessel type are spread over more partners and the cost allocated to each partner is lower than in the case of four partners. When comparing the results of five partners with those of three partners, it depends on the experiment and the partner considered whether the allocated cost is less than in the case with three partners and so, again, some partners could prefer a coalition of three partners. Therefore, the stability of these results are studied in the next paragraph. The second major difference is that the Shapley value now leads to allocation values differing from the decomposition method when equality of partners is assumed. This can be explained by the fact that the Shapley value rewards partners that contribute most to the collaborative goal. Since the partner Aalst-Antwerp has to perform the first part of the barge trajectory alone with the more expensive vessel type, its cost savings compared to the non-collaborative scenario become negative. As such, this partner has to make the most profound changes in its transport activities. The Shapley value accounts for this contribution by rewarding this partner with a higher share in the collaborative savings. In the five partner coalition, for example, Shapley allocates a savings percentage of 1.18% to Aalst Antwerp, compared to a savings percentage of 1.05% for the decomposition method.

To identify whether the cost allocations defined for the experiments with a shipment size of 273.6 tons guarantee cooperation stability, compliance of the proportional, decomposition and Shapley solutions with individual, subgroup and group rationality is verified. Since stability constraints are included in the EPM linear program, feasibility of the EPM solution indicates whether the grand coalition is stable. Analyzing cost allocations over all cases reveals that stability of the grand coalition is guaranteed in all three-partner collaborations. 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. In contrast, the core of all four-partner games is empty and thus none of the four-partner coalitions are stable. As the shipment sizes considered in this case study result in a significant amount of excess capacity for the more expensive vessel type, collaborating becomes detrimental for the partnering shippers. Stability of the five-partner coalitions depends on the equality of the partners. When collaborating shippers are equal in terms of shipment sizes, the core is non-empty. However, the grand coalition is stable only when EPM is used as allocation method. Collaborations set up between five shippers with different shipment sizes do not ensure long-term stability in this case study. Although stability cannot be guaranteed for all four-partner coalitions and five-partner coalitions, cost savings still need to be allocated fairly. In this context, EPM has been combined with the ε-core concept, as suggested by Frisk et al. (2010). Applying the ε-core, cooperation participants are penalized with a cost $\varepsilon > 0$ for quitting the grand coalition. In this way, stable cost allocations may be calculated for coalitions that do not satisfy the stability property. ε-EPM allocations are indicated in *italic* font in Tables 9 and 10. Although the ε-EPM also aims to minimize maximal pairwise differences between allocated transport cost savings, increased variation in partner savings is caused by adding ε-core constraints. To summarize, Table 11 provides an overview of which allocation mechanisms generate stable allocations, indicated by ✓, for each of the studied scenarios.

Table 11. Stability of scenarios with two shipment sizes

Scenario	Proportional	Decomposition	Shapley	EPM
3 equal partners	✓	✓	✓	✓
3 unequal partners	✗	✓	✓	✓
4 equal partners	✗	✗	✗	✗
4 unequal partners	✗	✗	✗	✗
5 equal partners	✗	✗	✗	✓
5 unequal partners	✗	✗	✗	✗

✓*: stable* allocations could be calculated

✗: no *stable* allocations could be calculated

5.2 Case study in the hinterland of the Port of Antwerp

In this case study, the impact of the number of partners, the equality of partners and the shipment frequency is examined. Similar to the ADA-based case study, the situation of three, four and five partners is investigated. For each of these coalition sizes, three scenarios are analyzed. First, it is assumed that all partners are equal in terms of shipment frequency. Scenario one examines allocation and stability results when the stand-alone frequency of the partners is maintained after bundling. In scenario two, the delivery frequency of the partners is doubled after bundling. In this way, the trade-off between allocated costs and customer service could be investigated in a multimodal collaboration context. Finally, in the third scenario it is assumed that coalition partners differ in terms of stand-alone frequency. Scenario three analyzes allocation and stability results when the shipment frequencies after bundling are equalized at the level of the highest stand-alone frequency. For each scenario, freight flows are destined to the Port of Antwerp (Figure 2).

Similar to the ADA-based case study, it is assumed that two vessel types are available: a vessel with a capacity of 96 TEU and a cost of 6€/km and a vessel with a capacity of 165 TEU and a cost of 9€/km. The smallest vessel is used first, only if the bundled freight exceeds its capacity, the larger vessel is utilized. As opposed to the first case study, shipment sizes of partnering shippers are not fixed in this second experiment. Partners are able to align their shipment frequencies z_i to increase the number of bundling opportunities and in this way improve collaborative synergy. However, as a consequence of this relaxed assumption, not only transport costs, but also order and inventory costs are influenced by the collaboration decision. Special attention thus needs to be paid to the fair savings division amongst the coalition partners and the stability of the allocation solutions obtained.

The results of the experiments with equal stand-alone frequencies are summarized in Tables 12 and 13. Table 12 shows the allocation results when the annual number of shipments is maintained after bundling (Scenario 1), while Table 13 visualizes the results when customer service has improved due to bundling (Scenario 2). Next, it is assumed that coalition partners differ in terms of stand-alone frequency. Table 14 summarizes the allocation results when the shipment frequencies after bundling are equalized at the level of the highest stand-alone frequency (Scenario 3). For clarification purposes, the 'SAF' column lists the stand-alone frequencies and the 'BF' column lists the frequencies after bundling. Analogue to the ADA-based case study, first the stand-alone cost (the cost without bundling) is given. Next, the results after bundling are provided for each partner using the proportional allocation method, the decomposition method, the Shapley value and the EPM.

Table 12. Results: equal stand-alone frequency, maintained service after bundling

	Firm-to-firm flow	SAF	BF	Stand-alone	Prop.	Decom-position	Shapley	(ε-)EPM
3 partners	Aalst-Antwerp	25	25	123650	119846	121005	119356	118036
	Zaventem-Antwerp	25	25	46308	42504	40239	41743	44205
	Mechelen-Antwerp	25	25	295062	291257	292363	292507	291365
4 partners	Aalst-Antwerp	25	25	123650	118868	119235	119157	118036
	Zaventem-Antwerp	25	25	46308	41525	39595	40810	44205
	Zaventem-Antwerp	25	25	152056	147273	148102	147291	146442
	Mechelen-Antwerp	25	25	295062	290279	291013	290687	289262
5 partners	Aalst-Antwerp	25	25	123650	118745	119060	118694	117215
	Zaventem-Antwerp	25	25	46308	41402	39531	40669	43898
	Zaventem-Antwerp	25	25	152056	147150	147864	147150	146749
	Mechelen-Antwerp	25	25	295062	290156	290537	290224	288955
	Mechelen-Antwerp	25	25	82023	77117	77577	77833	77753

Analyzing the allocation results of the second case study leads to the following insights. First, Tables 13 and 14 reveal that multimodal freight bundling may not only provide cost related benefits, but could also result in improved customer service. Both tables indicate that shippers are able to increase their shipment frequencies and at the same time enjoy cost savings due to the consolidation of shipments with partner organizations. However, when shippers decide to enhance their service level, they must be aware of the fact that this leads to a reduction in attainable cost savings. Shippers thus need to make a trade-off between offering more barge departures and incurring higher logistics costs. Moreover, considering coalitions of four and five partners, increased shipment frequencies are associated with empty cores and thus allocation results are non-stable irrespective of the applied allocation mechanism. This is demonstrated in Table 15 which provides an overview of the stability of the studied scenarios. When deciding on the offered service level, partnering shippers need to account for the stability properties of the applied allocation mechanism. Second, contrary to the ADA-based case study, each of the applied allocation mechanisms leads to unique results over all studied scenarios. Differences of 1.61%, on average, exist between 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. This is illustrated in Figure 5 in which the allocation results of the four methods on a coalition of three partners are shown. Third, results reveal that the applied cost allocation methods grant the largest relative benefit to the smallest partner Zaventem-Antwerp (Q = 400), while the largest partner Mechelen-Antwerp (Q = 3000) is allocated the lowest relative benefit in each of the studied scenarios (Figure 6). This is due to the fact that these partners experience the highest (Zaventem-Antwerp) and lowest (Mechelen-Antwerp) savings percentages consequential to bundling in comparison to their stand-alone costs. Moreover, while the partner Mechelen-Antwerp only takes part in one bund-

Table 13. Results: equal stand-alone frequency, improved service after bundling

	Firm-to-firm flow	SAF	BF	Stand-alone	Prop.	Decomposition	Shapley	(ε-)EPM
3 partners	Aalst-Antwerp	25	50	123650	121329	121582	121769	121799
	Zaventem-Antwerp	25	50	46308	43987	43393	43914	45614
	Mechelen-Antwerp	25	50	295062	292740	293081	292373	290643
4 partners	Aalst-Antwerp	25	50	123650	122184	122297	121615	*119748*
	Zaventem-Antwerp	25	50	46308	44842	44250	43227	*44846*
	Zaventem-Antwerp	25	50	152056	150590	150844	151849	*152056*
	Mechelen-Antwerp	25	50	295062	293595	293821	294521	*294561*
5 partners	Aalst-Antwerp	25	50	123650	121412	121556	121533	*119127*
	Zaventem-Antwerp	25	50	46308	44070	43217	42327	*44466*
	Zaventem-Antwerp	25	50	152056	149818	150144	149384	*150495*
	Mechelen-Antwerp	25	50	295062	292824	292998	294561	*295062*
	Mechelen-Antwerp	25	50	82023	79785	79995	80104	*78760*

Table 14. Results: unequal stand-alone frequency, improved and maintained service after bundling

	Firm-to-firm flow	SAF	BF	Stand-alone	Prop.	Decomposition	Shapley	(ε-)EPM
3 partners	Aalst-Antwerp	25	50	123650	120464	120227	121337	121123
	Zaventem-Antwerp	25	50	46308	43122	41484	43481	45361
	Mechelen-Antwerp	50	50	297656	294470	296345	293237	291572
4 partners	Aalst-Antwerp	25	50	123650	119602	119299	120754	*119663*
	Zaventem-Antwerp	25	50	46308	42260	39693	42366	*44176*
	Zaventem-Antwerp	50	50	159789	155741	155893	153566	*152433*
	Mechelen-Antwerp	50	50	297656	293608	296326	294525	*294938*
5 partners	Aalst-Antwerp	25	50	123650	119347	119126	121017	*119129*
	Zaventem-Antwerp	25	50	46308	42005	39628	41810	*43335*
	Zaventem-Antwerp	50	50	159789	155486	155658	150801	*151058*
	Mechelen-Antwerp	50	50	297656	293353	295856	294694	*295626*
	Mechelen-Antwerp	25	50	82023	77719	77641	79587	*78762*

led link, Zaventem-Antwerp bundles freight on two links of the barge trajectory. The remark could be made here that rewarding the partner who has added the smallest demand volume to the collaboration with the largest relative benefit may be perceived as unfair. Possibly, large shippers are not willing to collaborate considering the fact that they gain less than their smaller counterparts. For this reason, a fifth allocation method has been applied to the cost results of the second case study which takes the annual demand volumes of the partnering shippers into account. In Table 16 total collaborative savings are weighted with each participant's annual volume as follows:

$$y_i = w_i \cdot v(N) \qquad\qquad \forall i \in N \tag{7}$$

with $w_i = \frac{Q_i}{\sum_{i \in N} Q_i}$. In Table 16, the 'Scenario 1' column represents the allocations for the scenario in Table 12, 'Scenario 2' corresponds with the scenario in Table 13 and 'Scenario 3' lists the allocations for the scenario in Table 14. While these allocation values account for the demand contributions of the coalition partners, they do not guarantee stability. In line with the ε-core, a cost $\varepsilon > 0$ could be used to penalize cooperation participants for quitting the grand coalition. Fourth, EPM provides the most equally spread cost savings among the partners of the coalition for each of the studied scenarios, although increased variation in partner savings is caused by adding ε-core constraints. Finally, similar to the ADA-based case study, the coalition size needs to be aligned with the shipment sizes and vessel types available to ensure sufficient capacity utilization. For example, increasing the coalition size from three to four partners in the first scenario leads to a higher vessel fill rate and thus yields a higher savings percentage. However, increasing the coalition size from three to four partners in the second scenario results in the use of the larger, more expensive vessel type and thus reduces the savings percentage.

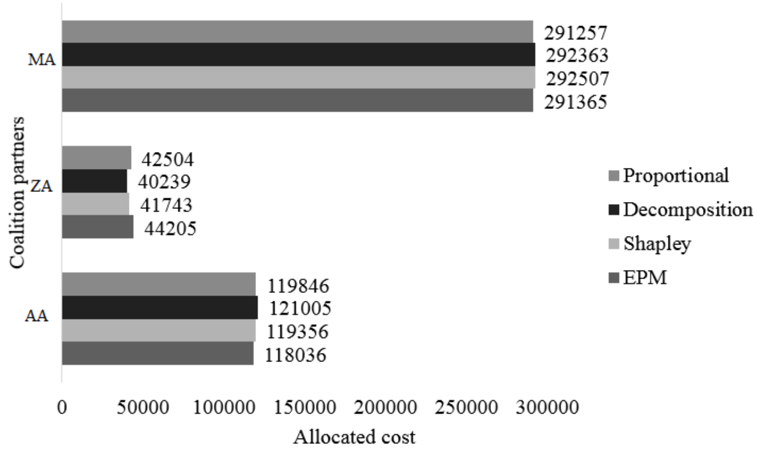

Figure 5. Cost allocation results for a coalition of three partners

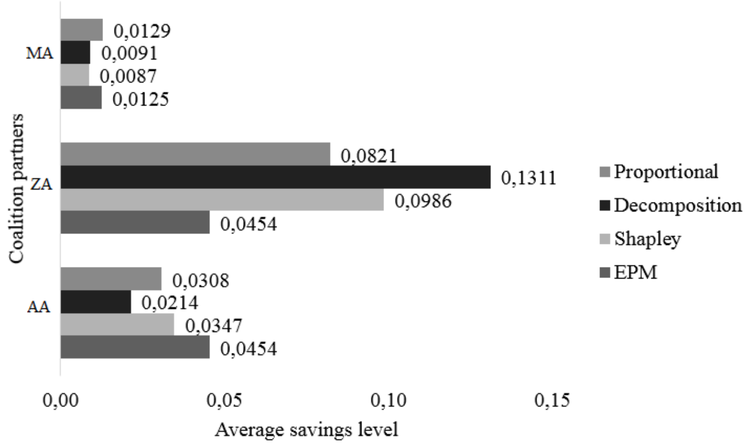

Figure 6. Average savings level (in %) for a coalition of three partners, with the smallest partner Zaventem-Antwerp being favored the most and the largest partner Mechelen-Antwerp being favored the least

Table 15. Stability of hinterland scenarios

Scenario	Proportional	Decomposition	Shapley	EPM
3 equal partners, SAF = BF	✗	✓	✓	✓
3 equal partners, SAF ≠ BF	✓	✓	✓	✓
3 unequal partners, SAF ≠ BF	✓	✓	✓	✓
4 equal partners, SAF = BF	✓	✓	✓	✓
4 equal partners, SAF ≠ BF	✗	✗	✗	✗
4 unequal partners, SAF ≠ BF	✗	✗	✗	✗
5 equal partners, SAF = BF	✓	✓	✓	✓
5 equal partners, SAF ≠ BF	✗	✗	✗	✗
5 unequal partners, SAF ≠ BF	✗	✗	✗	✗

✓*: stable* allocations could be calculated

✗: no *stable* allocations could be calculated

Table 16. Results: allocations based on annual shipment volume

	Firm-to-firm flow	Annual volume	Scenario 1	Scenario 2	Scenario 3
3 partners	Aalst-Antwerp	1100	120860	121948	121314
	Zaventem-Antwerp	400	45293	45689	45458
	Mechelen-Antwerp	3000	287453	290149	291284
4 partners	Aalst-Antwerp	1100	120143	122575	120682
	Zaventem-Antwerp	400	45033	45917	45229
	Zaventem-Antwerp	1500	147273	150590	155741
	Mechelen-Antwerp	3000	285496	292129	289560
5 partners	Aalst-Antwerp	1100	119682	121840	120170
	Zaventem-Antwerp	400	44865	45650	45042
	Zaventem-Antwerp	1500	146645	149588	155043
	Mechelen-Antwerp	3000	284240	290125	288163
	Mechelen-Antwerp	800	79137	80706	79491

6. Conclusions

Policy makers at European as well as regional levels express the need to stimulate multimodal transport chains. In order to improve the competitive position and efficiency level of multimodal transport, consolidation of freight flows is often suggested. Bundling networks require cooperation between multiple partners in the multimodal transport chain. In this context, the question rises how benefits may be allocated fairly among the participants in the cooperation. A great deal of scientific literature reports on the behavior of allocation methods in collaborations between shippers or carriers making use of unimodal transport. In multimodal barge transport various types of vessels with differing price structures may be considered for the bundling network. Moreover, the magnitude of the economies of scale resulting from consolidation in barge transport significantly exceeds that of the results obtained in road transport. As such, applying the allocation methods which have been thoroughly studied in a unimodal context is not so straightforward in a multimodal environment. In addition, research on cost or saving allocation methods in multimodal transport is scarce and focuses exclusively on the use of game theory. Practitioners consider the mathematical complexity of these techniques to be an impediment for their applicability in practice. The main contribution of this paper is to fill this research gap by comparing simple and straightforward allocation mechanisms with more advanced techniques based on game theory. For this purpose, four different allocation methods have been applied to two realistic case studies. By analyzing results in terms of savings division amongst the partners and collaborative stability, recommendations could be formulated to collaborating shippers on how they should tackle gain sharing decisions.

The first case study is carried out within the ADA framework and uses real data from a freight transport model for Flanders. Considering the scenarios with equal shipment sizes, Shapley allocations equal those of the decomposition method. If the partners are unequal in size, the decomposition method favors coalition partners that take part in more bundled links of the barge trajectory, while Shapley benefits partners with smaller shipment sizes. For the experiments with a shipment size of 273.6 tons, the use of a second, more expensive vessel type makes it important to look at the stability of the allocation results. Analyzing cost allocations over all cases reveals that stability of the grand coalition is guaranteed in all three-partner collaborations. In contrast, none of the four partner coalitions are stable. Stability of the five-partner coalitions depends on the equality of the partners.

Since the ADA assumptions may not always be realistic and could prevent shippers from optimally bundling their freight flows, a second case study, situated in the hinterland of the Port of Antwerp, is studied.

Results reveal that multimodal freight bundling may not only provide cost related benefits, but could also result in improved customer service. However, when deciding on the offered service level, partnering shippers need to account for the stability properties of the selected allocation mechanism. The allocation mechanisms applied in this chapter reward partners who experience the highest savings due to bundling. Small partners who previously had to bear high logistics costs in comparison to their low demand volumes, now enjoy the highest savings consequential to their engagement in the collaboration. Since large partners may consider this to be unfair, a fifth allocation method has been applied which takes the annual demand volumes of the partnering shippers into account.

When a decision has to be made on the mechanism of how to share collaborative savings in a multimodal barge context, it is important to use transparent methods in order to improve collaboration sustainability. Based on the findings in this paper, the following managerial insights may be formulated. For a limited number of partners, operationally simple cost sharing techniques like the proportional and/or decomposition mechanism may be utilized. Applying these straightforward techniques could reduce alliance complexity and enforce the strength of mutual partner relationships. The EPM provides the most equally spread cost savings. This characteristic may be particularly valuable in the early phases of a horizontal collaboration, in which having an initial allocation with similar benefits for all participating organizations may suit communication and negotiation purposes. Finally, it is important to think in advance about the number of coalition participants in combination with the size of the vessel. Different from the unimodal setting, adding more partners to the coalition is not always favorable, both in terms of stability and savings, since this might lead to the use of a larger (and more expensive) vessel. Moreover, while increasing the geographical coverage of the coalition improves collaborative efficiency in a unimodal setting, increased pre- and end-haulage reduces the level of collaborative savings in a multimodal context and may hamper the cost allocation decision. In summary, the nonlinear cost structure, the vessel size, the coalition size and the geographical coalition characteristics may be considered important drivers for profitability and allocation stability in a multimodal setting.

We acknowledge the limitations of the experimental study. The consideration of a distinct multimodal transport business model and the use of specific case study data (e.g. cost rates, vessel types, terminal locations, shipper locations) could influence the general validity of the findings. The conclusions, however, demonstrate the influence of cooperation characteristics on allocation results and underline the value of carefully selecting appropriate allocation mechanisms when long-term stability of the multimodal barge collaboration is aspired.

Several opportunities for future research on the multimodal allocation problem may be identified. One natural avenue of research is to add other cost allocation techniques from the literature to the experimental design or to develop allocation mechanisms especially suited in a multimodal environment. Next, a sensitivity analysis may be performed on the impact of the geographical case study characteristics. In this way, the influence of the terminal locations and the origin-destination locations, among others, on collaborative performance and cost allocation outcomes could be investigated. Third, our analysis could be extended to include other transport modes besides barge transport or could address the cost sharing decision in multimodal transport from a carrier perspective. Fourth, the focus of this paper was on analyzing the cost allocation problem in a multimodal barge context. However, results also reveal that partner characteristics may have a significant impact on collaboration outcomes. Future research work could thus investigate the impact of coalition features on the performance of multimodal collaborations. A final avenue for further research relates to the applicability and the use of these allocation techniques in different business model settings.

References

Bektas, T., Crainic, T.C., 2008. A brief overview of intermodal transportation. In: Taylor, G.D. (Ed.), Logistics Engineering Handbook. Boca Raton, FL: Taylor and Francis Group, chapter 28, pp. 1-16.

Ben-Akiva, M., de Jong, G., 2013. The Aggregate-Disaggregate-Aggregate (ADA) Freight Model System. In: Ben-Akiva, M., Meersman, H., Van de Voorde, E. (Eds.), Freight Transport Modelling. Bingley, U.K.: Emerald Group Publishing, chapter 4, pp. 69-90.

Braekers, K., Caris, A., Janssens, G.K., 2013. Optimal shipping routes and vessel size for intermodal barge transport with empty container repositioning. *Computers in Industry* 64(2), 155-164.

Caris, A., Limbourg, S., Macharis, C., van Lier, T., Cools, M., 2014. Integration of inland waterway transport in the intermodal supply chain: a taxonomy of research challenges. *Journal of Transport Geography* 41, 126-136.

Caris, A., Macharis, C., Janssens, G.K., 2011. Network analysis of container barge transport in the port of Antwerp by means of simulation. *Journal of Transport Geography* 19, 125-133.

Caris, A., Macharis, C., Janssens, G.K., 2012. Corridor network design in hinterland transportation systems. *Flexible Services and Manufacturing Journal* 24(3), 294-319.

Cruijssen, F., Dullaert, W., Fleuren, H., 2007. Horizontal cooperation in transport and logistics: a literature review. *Transport Journal* 46(3), 22-39.

De Jong, G., Ben-Akiva, M., 2007. A micro-simulation model of shipment size and transport chain choice. *Transportation Research Part B: Methodological* 41(9), 950-965.

European Commission, 2006. NAIADES Action Programme. Communication on the promotion of inland waterway transport.

European Commission, 2013. NAIADES II. Towards quality inland waterway transport.

European Commission, 2011. Transport White Paper: roadmap to a single European transport area – towards a competitive and resource efficient transport system, downloadable at: http://eur-lex.europa.eu/legal-content/en/ALL/?uri=celex%3A52011DC0144

Flóden, J., Sorkina, E., 2014. Business Models for Shipper-Operated Intermodal Transport Solutions. In: Macharis, C., Melo, S., Woxenius, J., van Lier, T. (Eds.), Sustainable Logistics (Transport and Sustainability, Volume 6). Bingley, U.K.: Emerald Group Publishing, chapter 8, pp. 193-215.

Flóden, J., Woxenius, J., 2017. Agility in the Swedish intermodal freight market - The effects of the withdrawal of the main provider. *Research in Transportation Business & Management* 23, 21-34.

Fragnelli, V., García-Jurado, I., Méndez-Naya, L., 2004. A note on bus games. *Economics Letters* 82(1), 99-106.

Frisk, M., Göthe-Lundgren, M., Jörnsten, K., Rönnqvist, M., 2010. Cost allocation in collaborative forest transportation. *European Journal of Operational Research* 205(2), 448-458.

Hesse, M., Rodrigue, J.P., 2004. The transport geography of logistics and freight distribution. *Journal of Transport Geography* 12(3), 171-184.

Hezarkhani, B., Slikker, M., Van Woensel, T., 2016. A competitive solution for cooperative truckload delivery. *OR Spectrum* 38 (1), 51-80.

Kim, N.S., Van Wee, B., 2011. The relative importance of factors that influence the break-even distance of intermodal freight transport systems. *Journal of Transport Geography* 19, 859-875.

Konings, R., Kreutzberger, E., Maras, V., 2013. Major considerations in developing a hub-and-spoke network to improve the cost performance of container barge transport in the hinterland: the case of the port of Rotterdam. *Journal of Transport Geography* 29, 63-73.

Kreutzberger, E., 2010. Lowest cost intermodal rail freight transport bundling networks: conceptual structuring and identification. *European Journal of Transport and Infrastructure Research* 10(2), 158-180.

Kreutzberger, E., Konings, R., 2013. Twin hub network: an innovative concept to boost competitiveness of intermodal rail transport to the hinterland. Proceedings of the TRB 92nd annual meeting, Transportation Research Board.

Lehtinen, J., Bask, A.H., 2012. Analysis of business models for potential 3Mode transport corridor. *Journal of Transport Geography* 22, 96-108.

Liu, P., Wu, Y., Xu, N., 2010. Allocating collaborative profit in less-than-truckload carrier alliance. *Journal of Service Science and Management* 3(1), 143-149.

Maes, T., Ramaekers, K., Caris, A., Janssens, G.K., Bellemans, T., 2011. Simulation of logistic decisions within a freight transportation model. Proceedings of the Industrial Simulation Conference, pp. 185-191.

Meers, D., Vermeiren, T., Macharis, C., 2014. Intermodal Break-Even Distances: A Fetish of 300 Kilometres? In: Macharis, C., Melo, S., Woxenius, J., van Lier, T. (Eds.), Sustainable Logistics (Transport and Sustainability, Volume 6). Bingley, U.K.: Emerald Group Publishing, chapter 9, pp. 217-243.

Miller, H.J., 2013. Beyond sharing: cultivating cooperative transportation systems through geographic information science. *Journal of Transport Geography* 31, 296-308.

Notteboom, T.E., 2007. Inland waterway transport of containerized cargo: from infancy to a full-fledged transport mode. *Journal of Maritime research* 4(2), 63-80.

Notteboom, T.E., Rodrigue J.-P., 2005. Port regionalization: towards a new phase in port development. *Maritime Policy and Management* 32(3), 297-313.

Özener, O.Ö., Ergun, Ö, 2008. Allocating costs in a collaborative transportation procurement network. *Transportation Science* 42(2), 146-165.

Panteia/NEA, Erasmus Universiteit, TNO, 2013. Eindrapportage onderzoekscluster 3 – Actieplan - Afstemming in de keten.

Ramaekers, K., Verdonck, L., Caris, A., Meers, D., Macharis, C., 2016. Analysis of cost allocation techniques for freight bundling networks in intermodal transport. In: Paias, A., Ruthmair, M., Voss, S. (Eds.), Computational Logistics: 7th International Conference, ICCL 2016, Lisbon, Portugal, September 7-9, 2016, Proceedings. Switzerland: Springer International Publishing, pp. 209-226.

Schmeidler, D., 1969. Nucleolus of a characteristic function game. *Siam Journal on Applied Mathematics* 17(6), 1163-1170.

Shapley, L., 1952. Notes on the n-person game, III: some variants of the Von- Neumann-Morgenstern definition of solution. RAND Corporation Research Memorandum, RM-817.

Shapley, L.S., 1953. A value for n-person games. In: Kuhn, H., Tucker, W. (Eds.), Contributions to the Theory of Games. Princeton: Princeton University Press, pp 31-40.

Soons, D., 2011. The determination and division of benefits among partners of a horizontal cooperation in transportation. Master’s thesis, TU/e School of industrial engineering, Eindhoven, the Netherlands.

Tavasszy, L.A., Behdani, B., Konings, R., 2015. Intermodality and Synchromodality, downloadable at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2592888

Theys, C., Dullaert, W., Notteboom, T.E., 2008. Analyzing cooperative networks in intermodal transportation: a game-theoretic approach. Nectar Logistics and Freight Cluster Meeting, Delft, the Netherlands.

Tijs, S.H., Driessen, T.S.H., 1986. Game theory and cost allocation problems. *Management Science* 32(8), 1015-1028.

Trip, J.J., Bontekoning, Y., 2002. Integration of small freight flows in the intermodal transport system. *Journal of Transport Geography* 10, 221-229.

Van den Berg, R., 2015. Strategies and new business models in intermodal hinterland transport, downloadable at: https://pure.tue.nl/ws/files/13118317/20160615_Berg_van_den.pdf

van Lier, T., Caris, A., Macharis, C., 2016. Sustainability SI: Bundling of outbound freight flows: Analyzing the potential of internal horizontal collaboration to improve sustainability. *Networks and Spatial Economics* 16(1), 277-302.

van Riessen, B., Negenborn, R.R., Dekker, R., 2015. Synchromodal container transportation: An overview of current topics and research opportunities. In: Corman, F., Voss, S., Negenborn, R.R. (Eds.), Computational Logistics: 6th International Conference, ICCL 2015, Delft, the Netherlands, September 23-25, 2015, Proceedings. Switzerland: Springer International Publishing, pp. 386-397.

Vanovermeire, C., 2014. Horizontal collaboration in logistics: Increasing efficiency through flexibility, gain sharing and collaborative planning. PhD thesis, University of Antwerp, Antwerp, Belgium.

Verdonck, L., 2017. Collaborative logistics from the perspective of freight transport companies. PhD thesis, Hasselt University, Diepenbeek, Belgium.

Verdonck, L., Beullens, P., Caris, A., Ramaekers, K., Janssens G.K., 2016. Analysis of collaborative savings and cost allocation techniques for the cooperative carrier facility location problem. *Journal of the Operational Research Society* 67(6), 853-871.

Verdonck, L., Caris, A., Ramaekers, K., Janssens G.K., 2013. Collaborative logistics from the perspective of road transportation companies. *Transport Reviews* 33(6), 700-719.

Woxenius, J., 2007. Generic Framework for Transport Network Designs: Applications and Treatment in Intermodal Freight Transport Literature. *Transport Reviews* 27(6), 733-749.

Xu, X., Pan, S., Ballot, E., 2013. A sharing mechanism for superadditive and non-superadditive logistics cooperation. Proceedings of the International Conference on Industrial Engineering and System Management, pp. 789-795.