ORIGINAL ARTICLE

Generating greenhouse gas cutting incentives when allocating carbon dioxide emissions to shipments in road freight transportation

Florian Kellner[1]

Abstract

Road freight transportation accounts for a great share of the anthropogenic greenhouse gas (GHG) emissions. In order to provide a common methodology for carbon accounting related to transport activities, the European Committee for Standardization has published the European Norm EN-16258. Unfortunately, EN-16258 contains gaps and ambiguities and leaves room for interpretation, which makes the comparison of the environmental performance of different logistics networks still difficult and hinders the identification of best practices. This research contributes to the identification of particularly meaningful principles for the allocation of GHG to shipments in road freight transportation by presenting an analytical framework for studying the performance of the EN-16258 allocation schemes with respect to accuracy, fairness, and the GHG minimizing incentive. In doing so, we continue previous studies that analyzed two important aspects of the EN-16258 allocation rules: accuracy and fairness. This study provides further insights into this allocation problem by investigating the incentive power of the different allocation schemes to opt for the GHG minimal way of running a road freight network. First, we complement the list of transport scenarios introduced in prior studies and present two novel scenarios. Second, we carry out a series of numerical experiments to compare the EN-16258 allocation rules with respect to accuracy, fairness, and the GHG minimizing incentive. We find that the results may differ significantly for the two scenarios, suggesting a case-by-case recommendation. This is particularly interesting because the first scenario confirms the results of the prior studies, while the second scenario rather contradicts them.

Keywords GHG allocation · Road freight transportation · Cooperative game theory · EN-16258

✉ Florian Kellner
 florian.kellner@ur.de

1 Faculty of Business, Economics and Management Information Systems, University of Regensburg, Universitätsstraße 31, 93053 Regensburg, Germany

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1 Introduction

Societies around the globe increasingly notice the effects of climate change, including extreme weather conditions, droughts, the melting ice of glaciers, and rising sea levels. Among scientists, politicians and in the population, there is a broad consensus that anthropogenic greenhouse gas (GHG) emissions are a major contributor to the global warming and that there is the urgent need to respond to the threat of climate change by limiting the global temperature rise in the forthcoming years (Cook et al. 2016). A central element to achieve this is the reduction of GHG caused by the combustion of fossil fuels (IPCC 2007; UNFCCC 2018; USEPA 2018).

According to the European Environment Agency and the US Environmental Protection Agency, road freight transportation accounts for a great share of the anthropogenic GHG emissions: both in the EU-28 and in the USA, the movement of trucks contributes to around 7% of the total emissions (EEA 2019; USEPA 2019). In a white paper on transport, the European Commission states that the transport sector has to cut emissions by around 60% until 2050, compared with the level of 1990, to achieve the global goal of overall GHG reductions of 80–95% (EC 2016).

In order to guarantee an accurate, transparent, and comparable quantification of GHG resulting from transport activities, the European Committee for Standardization has published in 2012 the European Norm EN-16258 'Methodology for calculation and declaration of energy consumption and GHG emissions of transport services.' The intention of this norm is to provide a common methodology for carbon accounting, which is a precondition for the comparison of the environmental performance of different logistics networks, for the assessment of the emission efficiency of alternative logistics strategies and processes, and for the identification of GHG cutting opportunities and best practices. EN-16528 specifies general principles, definitions, system boundaries, calculation methods, apportionment rules (allocation) and data recommendations, with the objective to promote standardized, accurate, credible and verifiable declarations, regarding energy consumption and GHG emissions related to any transport service quantified (CEN 2012). Among a couple of GHG accounting guidelines published by different organizations (cf. COFRET 2011, 2015), EN-16258 holds a special position as it constitutes the only official international standard for emission calculation of transport activities. The standardization institutes of 33 European countries are obliged to accept EN-16258. Unfortunately, as has been shown in different studies, the current version of EN-16258 contains some gaps and ambiguities and leaves at different places room for interpretation. This makes the comparison of the environmental performance of different supply chains still difficult and hinders the identification of best practices (Auvinen et al. 2014; Davydenko et al. 2014; Kellner 2016).

This research is intended to overcome the ambiguities of EN-16258 in the area of the allocation of GHG emissions to shipments in road freight transportation (EN-16258: chapter 8). In detail, we continue previous research projects that

analyzed the EN-16258 allocation rules with respect to different aspects and in different road freight transport scenarios with the intention to identify particularly meaningful allocation rules—which will then be recommended as standard rules for upcoming versions of EN-16258.

Recently, Kellner and Schneiderbauer (2019) applied concepts of the cooperative game theory (CGT) to different vehicle routing scenarios in a numerical study to analyze the performance of the EN-16258 allocation rules with respect to two important aspects: accuracy and fairness. Our research provides further insights into this allocation problem by focusing on another important aspect that should be taken into consideration when recommending the most meaningful allocation unit to distribute GHG emissions to shipments: the incentive power of the different allocation schemes to opt for the GHG minimal way of running a road freight transport network. Consider, for instance, an industrial company that may choose one from several logistics service providers (LSP) to move its products from the factories to its customers. Or consider a customer that may choose one among several suppliers from which it sources the desired goods. In those cases, we rate it as undesired if an allocation rule assigns less GHG to this industrial company/customer when the decision for a certain LSP/supplier increases the overall GHG of the logistics network. In such a case, the considered allocation rule points to the wrong alternative and incentivizes to behave not in line with the fundamental goal to minimize GHG as much as possible. In summary, we start from the point of view that a GHG allocation principle should incorporate four fundamental characteristics:

(a) it should be *easily applicable*, allowing a wide range of users to apply them to compare different logistics strategies. Applicability implies that an allocation principle is based on easily determinable characteristics that any shipment inherits, such as its weight or volume; these characteristics then serve as the unit of allocation. Approaches coming with data collection problems or with a huge computational effort, such as some game theory approaches, are less suitable.

(b) it should allocate *accurately*, i.e., according to the polluter-pays principle, thereby reflecting the causal relationship between the transport process and GHG generation. Accuracy is to reflect the extra GHG that are generated when a shipment is added to a transport scenario. Specifically, we consider an allocation principle as accurate if it allocates GHG proportional to a weighted average of the marginal GHG contributions of the single shipments to all possible coalitions of the other shipments.

(c) it should allocate in a way that is perceived as '*fair*' by the parties concerned, as rules that are perceived as 'arbitrary' or 'unfair' will reduce their acceptance and jeopardize the transport cooperation. Certainly, fairness perceptions vary from one individual to another. In this research, we investigate the performance of different allocation schemes using a set of game theoretical fairness criteria that will be important and comprehensible to any player. An illustrative example for a situation that may be seen as unfair is when a single shipment or a group of shipments gets more GHG allocated than it would receive when not joining the 'transport cooperation,' i.e., when being delivered separately.

(d) it should *reward* parties that take decisions that *minimize the overall GHG* of a logistics network. Or, put it differently: an allocation principle should not allocate less GHG to an individual (e.g., a supplier, a customer) when this individual makes a decision that increases the overall GHG emissions of the transport operation.

In summary, the contribution of this research is twofold: (1) We carry on the analyses of the performance of the EN-16258 allocation rules in distinct road freight transport scenarios that have been initiated by prior research projects and study an aspect that we consider as being absolutely relevant and that has not been studied before: the GHG minimizing incentive of the different EN-16258 allocation rules. For this purpose, we complement the list of transport scenarios introduced by the prior research projects and present two novel scenarios. These scenarios do not only allow studying the aspects that prior research already analyzed (accuracy and fairness), but also the incentive power to opt for the GHG minimal way of running a road freight transport network. (2) We present the setup and the results of a series of numerical experiments that compare the performance of the EN-16258 allocation rules with respect to accuracy, fairness, and GHG minimizing incentive. The criteria used to analyze the EN-16258 allocation rules are largely based on the concepts of the CGT. Kellner and Schneiderbauer (2019) call the study of the allocation of GHG emissions to shipments in vehicle routing settings based on concepts of the CGT the 'pollution routing game (PRG).' This study adds a novel aspect to this problem.

The remainder of the paper is organized as follows: Sect. 2 reviews the relevant literature. Section 3 introduces two transport scenarios and a CGT based framework for the analysis of the EN-16258 allocation rules. Section 4 presents a numerical study intended to identify the EN-16258 allocation unit that balances best the aspects 'accuracy,' 'fairness,' and 'GHG minimizing incentive.' Finally, Sect. 5 recaps the results and provides recommendations for future research.

2 Literature review

The literature review consists of three parts. The first part (Sect. 2.1) presents the object of investigation, i.e., the principles that EN-16258 specifies for the allocation of GHG emissions to shipments in road freight transportation. Section 2.2, then, reviews research that analyzed the EN-16258 allocation rules and that made suggestions on how to improve the norm. And Sect. 2.3 highlights the contribution of this study to the body of research.

2.1 The EN-16258 GHG allocation principles

EN-16258 (CEN 2012) specifies various principles for the preparation of emission declarations of transport services. The apportionment rules for the allocation of GHG emissions to shipments in road freight transportation are defined in chapter 8. According to these principles, shipment-level GHG are calculated in two

consecutive steps: (1) the GHG volume of a transport service is determined; (2) this quantity is allocated to the single shipments that jointly make use of the transport service.

2.1.1 Step1: determining the volume of GHG of a transport operation

First, the total amount of GHG resulting from a transport service is determined. According to EN-16258, the emissions have to be determined on the basis of the 'vehicle operating system (VOS),' which is defined as a consistent set of vehicle operations carried out to move the relevant shipments. An important aspect of the VOS concept is that all empty trips related to the transport operation have to be taken into consideration. This aspect is relevant in our research as the CGT framework applied requires the determination of GHG for the transport operations of each possible sub-coalition that may be formed by the shipments that request service. After the vehicle operating system has been defined, the fuel consumption of the VOS is determined. Finally, an emission conversion factor (ECF) is used to translate the quantity of combusted fuel into GHG. EN-16258 indicates that the ECF for the combustion of one liter diesel is 2.67 kg CO_2e (carbon dioxide equivalents).

Whereas EN-16258 specifies that GHG from transportation are to be calculated by multiplying the quantity of combusted fuel with an energy conversion factor, the norm does not provide any details on how fuel consumption should be determined. As the direct measurement of the fuel consumption of a transport operation is often not possible, so-called 'fuel consumption models' have been developed. These models estimate the fuel consumption of a transport operation based on a variety of vehicle, environment, and traffic-related parameters, such as vehicle speed, load factors, road gradients, and acceleration (Demir et al. 2014). A broadly accepted approach, both in research and in practice, is to interpolate the fuel consumption of an empty and a completely loaded truck (Guajardo 2018). Several institutions engaged in environmental protection, including those having participated in the development of EN-16258 (ADEME 2010; DECC 2015; ifeu 2014; Kranke et al. 2011; Schmied and Knörr 2012), suggest Eq. (1) for the approximation of the fuel consumption of a road freight transport operation.

$$FC = \left(FC_{empty} + \left(FC_{full} - FC_{empty} \right) * \frac{to}{Capa} \right) / 100 * distance \qquad (1)$$

According to Eq. (1), the fuel consumption of a transport operation FC is calculated by multiplying the vehicle fuel consumption per kilometer and the *distance* travelled. The vehicle's fuel consumption per 100 km is interpolated based on the vehicle specific fuel consumption when it is fully loaded (FC_{full}), when it is empty (FC_{empty}), and based on the weight-based load factor ($to/Capa$). *to* represents the tonnage transported on the considered transport leg and *Capa* the maximum

weight-based vehicle payload capacity. Representative values for FC_{empty}, FC_{full}, and *Capa* are provided, for example, by ifeu (2018), INFRAS (2011), and Kranke et al. (2011).

2.1.2 Step2: allocating the GHG emissions to the shipments

After the total amount of GHG of the transport operation has been determined, it can be allocated to the shipments. EN-16258 allows various allocation units but names 'Ton-kilometer' as the default. Thus, the basis for the GHG allocation is the product of the shipment weight and the real travelled distance of the single shipments. For collection and distribution round-trips, EN-16258 specifies a different approach: in the round-trip case, the distance is not represented by the real travelled distance but either by the great circle distance or by the shortest feasible distance. Concerning the allocation unit, EN-16258 allows other units than 'Ton-kilometer,' but there is no further specification for when and where which allocation unit should be applied. The complete set of allocation units named in EN-16258 (CEN 2012) is summarized in Table 1.

2.2 Appraisal of the EN-16258 allocation principles

Although some time has passed since the appearance of EN-16258, there are only a few studies that criticize the norm and that make suggestions for its improvement. This is surprising since several research projects are based on the EN-16258 principles (e.g., Jevinger and Persson 2016; Kirschstein and Bierwirth 2018) and since there are some researchers who consider the European norm as a starting point for a global standard for emission calculation and declaration (COFRET 2015; Davydenko et al. 2014; Kellner and Schneiderbauer 2019; Kirschstein and Bierwirth 2018). Concerning the EN-16258 allocation principles (cf. Table 1), there are in particular two aspects that may be criticized: the two trip types and the five allocation units.

Auvinen et al. (2014), Davydenko et al. (2014), and Kellner (2016) criticize, amongst others, a lack of fairness with regard to the GHG apportionment principles. To be precise, Davydenko et al. (2014) and Kellner (2016) explicitly refer to the two trip types and state that the use of the real travelled distances, as in the case of the standard trip, allocates in a way that may be perceived as 'unfair' by shippers and consignees. The authors argue that some shipments travel the most direct routes, whereas others are moved additional kilometers only due to the carriers' routing decisions. That is, in the case of the standard method, the allocation is rather based on the routing decisions of the logistics service provider than on the characteristics of the single shipments. Such an allocation can be seen as unfair (cf. Fishburn 2005; Fishburn and Pollak 1983; Zhu et al. 2014). As a consequence, the authors recommend that the standard trip allocation scheme should be removed from EN-16258 and that direct distances should not only be used for the allocation of GHG from collection and distribution trips but for any transport operation. In this research, we

Table 1 Allocation units named in EN-16258 (CEN 2012)

Allocation unit	Standard trip	Round-trip (delivery/collection trip)
Ton-kilometer (default)	– Ton: shipment weight	– Ton: shipment weight
	– Kilometers: real travelled distance	– Kilometers: great circle distance or shortest feasible distance
Volume-kilometer	– Volume: pallet, parcel, TEU, etc	– Volume: pallet, parcel, TEU, etc
	– Kilometers: real travelled distance	– Kilometers: great circle distance or shortest feasible distance
Ton	Shipment weight	Shipment weight
Volume	Cubic meter, palette, TEU, etc	Cubic meter, palette, TEU, etc
Kilometer	Distance travelled, great circle distance, or shortest feasible distance	Great circle distance or shortest feasible distance

adopt this finding and concentrate exclusively on the round-trip allocation scheme (Table 1: rightmost column).

Concerning the five allocation units, Davydenko et al. (2014) suggest replacing 'ton' with 'allocation weight,' which they define as a single parameter bringing together multiple vehicle capacity related dimensions. The authors argue that this parameter better reflects a shipment's claim on a vehicle's capacity. Kellner (2016) suggests that there should be only one allowed allocation unit in EN-16258 because this guarantees the comparability of GHG assessments of supply chains. He believes that the proposed allocation rule should combine two aspects as well as possible: accuracy and pragmatism. Pragmatism is important as this makes sure that an allocation rule can be applied by many users. This, in turn, is a precondition for the comparative assessment of several logistics networks. In order to identify the most meaningful allocation principle, he preselects the allocation rules named in EN-16258 (which guarantees pragmatism) and compares the outcome of the single rules with the Shapley value in a numerical study. The transport scenarios ('games') studied by Kellner (2016) are transport routes starting and ending at a depot, i.e., he studies a travelling salesman setting. In total, he simulates 200 round trips (delivery trips where shipments are only distributed but not collected) with a number of shipments between 2 and 9. The results show that the allocation vectors based on 'Kilometer' are most often in line with the Shapley value. In addition, Kellner (2016) recommends that 'Kilometer' should only be represented by the great circle distance, and not by either the great circle or the shortest feasible distance. Kellner and Schneiderbauer (2019) focus on the five round trip allocation units (Table 1: rightmost column) and analyze in a numerical study the performance of the EN-16258 allocation units in three vehicle routing scenarios. The games studied are a vehicle routing problem with pick-ups and deliveries, a network flow model where several customers order distinct products at multiple suppliers, and a mixed scenario combining the first two models and using a myopic shipment routing approach (routing decisions are made sequentially at the different locations) instead of mathematical optimization. Kellner and Schneiderbauer (2019) analyze the performance of the EN-16258 allocation schemes in 99 vehicle routing problems, 50 network flow models, and 100 mixed models. They use CGT concepts to compare the allocation rules with respect to pragmatism, accuracy, and different CGT fairness criteria. Their study extends the prior research projects that addressed the allocation of GHG emissions to shipments (e.g., Guajardo 2018; Kellner 2016; Kellner and Otto 2012; Leenders et al. 2017; Naber et al. 2015) because it does not study the GHG allocation problem in a travelling sales man setting, i.e., with fixed tours, but in several vehicle routing scenarios. This allows the authors to take the physical effect of a shipment on GHG into account but also the fact that shipment characteristics in terms of origin, destination, weight, and volume consume transport capacities to different degrees, thus, impact the routing of several vehicles at the same time and, thus, determine GHG. They introduce the study of the allocation of GHG emissions to shipments in vehicle routing settings as the 'pollution routing game.' Their results indicate that the allocation unit 'Kilometer' bridges best the trade-off between accuracy, fairness, and convenience.

2.3 Contribution to the literature

This study carries on the analyses of the performance of the EN-16258 allocation rules in distinct road freight transport scenarios that have been initiated by prior research projects. In particular, we proceed the study of Kellner and Schneiderbauer (2019) by adding a novel aspect to the pollution routing game: the incentive power of the different allocation schemes to opt for the GHG minimal way of running a road freight transport network. In their conclusion, Kellner and Schneiderbauer (2019) suggest that future research should extend the analysis of the PRG by introducing new transport scenarios that reflect a specific transport context and that more CGT concepts should be used to study the allocation problem more in depth. Our research directly replies to this call for research by introducing two new transport scenarios for the PRG, by adding a new aspect to it, and by proposing a framework for studying this aspect. We believe that the GHG minimizing incentive is absolutely relevant when searching for the most meaningful allocation unit to distribute GHG to shipments. For this purpose, we present two novel transport scenarios that do not only allow studying the aspects that prior research analyzed (pragmatism, accuracy, fairness), but also the incentive power to opt for the GHG minimal way of running a road freight network. In doing so, we implicitly verify if the observations made in the prior studies are also valid in the new, extended transport scenarios. The developed scenarios are network-flow/vehicle-routing problems as this allows us not only taking the physical effect of a shipment on GHG into account but also the fact that the single shipments consume transport capacities to different degrees, impact the routing of the vehicles and thus affect GHG from transportation (Kellner and Schneiderbauer 2019).

As our research extends the pollution routing game, we implicitly contribute to the stream of research that studied the 'vehicle routing game' (Göthe-Lundgren et al. 1996)—whereas, in this research, GHG is the object of allocation and not costs. Guajardo and Rönnqvist (2015) find that the use of CGT is well established in the literature on transport cost allocation (e.g., Defryn et al. 2016; Engevall et al. 1998, 2004; Frisk et al. 2010; Krajewska et al. 2008; Lozano et al. 2013; Matsubayashi et al. 2005; Ozener and Ergun 2008; Potters et al. 1992; Yengin 2012). Though, according to Guajardo (2018), its use for GHG allocation is incipient.

3 Methodology

3.1 General approach: overview of the pollution routing games

In order to identify the most meaningful allocation unit among all possibilities listed in EN-16258, we carry out a series of numerical experiments where we compare the performance of the single allocation units with respect to three aspects: (a) accuracy, (b) fairness, and (c) the GHG minimizing incentive. All scenarios studied
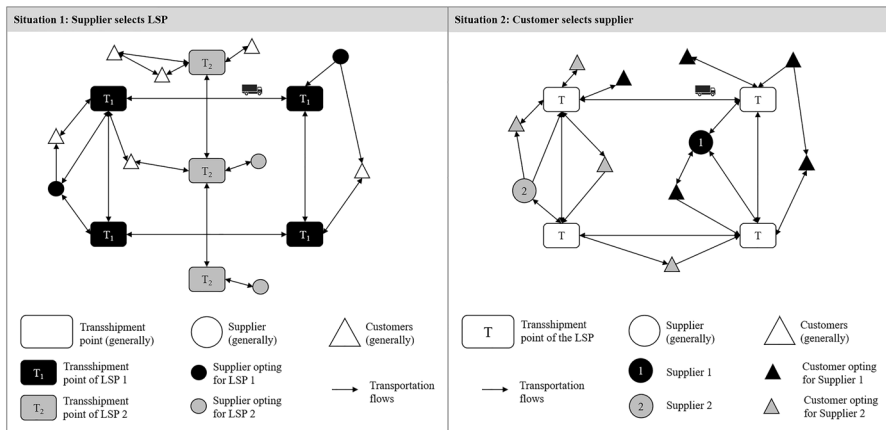
Fig. 1 Overview: Transport scenarios

correspond to a network-flow/vehicle-routing setting, i.e., there is a set of customers who are ordering products at a set of suppliers and it has to be decided what paths the products take through a transport network operated by one or several logistics service providers and consisting of several consolidation/transshipment points. The proposed scenarios may be subdivided into two decision situations (Fig. 1), reflecting typical decision situations in transport planning:

(1) Situation 1: In the first situation, there are several customers who are placing orders for distinct products at the corresponding suppliers and each supplier may nominate one from several available LSPs to move its products to the single customers. Note that, in the situation studied, each supplier selects exactly one LSP for moving all of its products to the customers.

(2) Situation 2: In the second situation, there are several customers with a demand for a certain product and each customer may choose a certain supplier from who this product will be sourced.

3.2 Presentation of the transport scenarios

3.2.1 Scenario 1: Supplier selects carrier

Scenario 1 reflects a situation where several customers are placing orders for distinct products at different suppliers. Each supplier produces a certain product and the customers are ordering different quantities of these products. The goods are routed through transport networks operated by different logistics service providers. These LSP networks differ in the number and the geographical locations of the transshipment points, where the goods can be (re)-consolidated. Each supplier may nominate one from several available LSPs to move all of its products to the single customers.

The proposed network flow model reflects this situation and incorporates the three factors that are also used in EN-16258 as allocation units, namely 'distance'

and the vehicle capacity limiting factors 'shipment weight' and 'shipment volume.' The reason for this is the fact that we want to observe how these factors determine GHG emissions while not only taking their physical effect on GHG into account but also their effect on the routing of the shipments and, thereby, on GHG.

Let $G = (V, A)$ be a graph consisting of a set of vertices V and arcs A. V consists of the set of suppliers S, customers C, and transshipment points T ($V = S \cup C \cup T$). Furthermore, there is the set of the products P and the set of the LSPs L. Note that $T = \bigcup_{l \in L} T_l$. Finally, there is a set of vehicles/routes R, which allows each LSP to use a certain arc of the transport network more than one time to move cargo over a certain link. EN-16258 specifies that any VOS must include all empty trips required to serve the transport requests. Thus, before cargo can be collected at a certain supplier, an empty trip is necessary to reach this supplier. Furthermore, after delivering cargo to a customer, the empty vehicle is routed back to one of the transshipment points.

Indices

$t \in T = T_1 \cup T_2 \cup \dots$	Transshipment points of LSP 1, 2 …
$h, i, j \in V = S \cup C \cup T$	Nodes representing suppliers, customers, and transship. points
$p \in P$	Products produced by the suppliers
$l \in L$	Logistics Service Providers
$r \in R$	Vehicles/Routes

Decision variables

$y_{pl} \in \{0;1\}$	Equals 1 if LSP l is nominated to move product p, and 0 otherwise
$x_{ijrl} \in \{0;1\}$	Equals 1 if arc (i,j) is traversed in route r by LSP l, and 0 otherwise
$t\_w_{ijrl} \in R^+$	Transported weight from location i to j in route r with LSP l
$t\_w\_p_{ijrlp} \in R^+$	Transp. weight of product p from loc. i to j with LSP l in route r
$t\_v_{ijrl} \in R^+$	Transported volume from location i to j in route r with LSP l
$t\_v\_p_{ijrlp} \in R^+$	Transp. vol. of product p from loc. i to j with LSP l in route r

Parameters

$dist_{ij} \in R^+$	Distance between location i and j
$s\_w_{ip} \in R^+$	Weight-based supply of supplier i regarding product p
$d\_w_{ip} \in R^+$	Weight-based demand of customer i regarding product p
$vol_p \in R^+$	Volume of product p, indicated in kilogram per pallet
$max\_Weight \in R^+$	Maximum weight-based payload
$max\_Vol \in R^+$	Maximum volume-based payload
$FC_{empty} \in R^+$	Vehicle fuel consumption when empty (liters per 100 km)
$FC_{full} \in R^+$	Vehicle fuel consumption when fully loaded (liters per 100 km)

$$ECF \in R^+ \qquad \text{Emission conversion factor (2.67 kg } CO_2 \text{ equivalents/liter diesel)}$$

Objective

$$min \sum_{i,j \in V, r \in R, l \in L} \left(FC_{empty} * \frac{dist_{ij}}{100} * ECF * x_{ijrl} + \left(FC_{full} - FC_{empty} \right) * \frac{t\_w_{ijrl}}{max\_Weight} * \frac{dist_{ij}}{100} * ECF \right) \qquad (2)$$

Constraints

$$\sum_{l \in L} y_{pl} = 1 \quad \forall p \in P \qquad (3)$$

$$t\_w\_p_{ijrlp} \leq y_{pl} * max\_Weight \quad \forall i,j \in V, r \in R, l \in L, p \in P \qquad (4)$$

$$x_{ijrl} = 0 \quad \forall i \in V, j \in T_x, r \in Rl \in L/\{x\} \qquad (5)$$

$$x_{ijrl} = 0 \quad \forall i \in T_x, j \in V, r \in Rl \in L/\{x\} \qquad (6)$$

$$\sum_{j \in V, r \in R, l \in L} t\_w\_p_{ijrlp} - \sum_{h \in V, r \in R, l \in L} t\_w\_p_{hirlp} \leq s\_w_{ip} \quad \forall i \in S, p \in P \qquad (7)$$

$$\sum_{j \in V, r \in R, l \in L} t\_w\_p_{ijrlp} - \sum_{h \in V, r \in R, l \in L} t\_w\_p_{hirlp} = -d\_w_{ip} \quad \forall i \in C, p \in P \qquad (8)$$

$$\sum_{j \in V, r \in R, l \in L} t\_w\_p_{ijrlp} - \sum_{h \in V, r \in R, l \in L} t\_w\_p_{hirlp} = 0 \quad \forall i \in T, p \in P \qquad (9)$$

$$t\_w_{ijrl} = \sum_{p \in P} t\_w\_p_{ijrlp} \quad \forall i,j \in V, r \in R, l \in L \qquad (10)$$

$$t\_v_{ijrl} = \sum_{p \in P} t\_v\_p_{ijrlp} \quad \forall i,j \in V, r \in R, l \in L \qquad (11)$$

$$t\_v\_p_{ijrlp} = t\_w\_p_{ijrlp}/vol_p \quad \forall i,j \in V, r \in R, l \in L, p \in P \qquad (12)$$

$$t\_w_{ijrl} \leq max\_Weight * x_{ijrl} \quad \forall i,j \in V, r \in R, l \in L \qquad (13)$$

$$t\_v_{ijrl} \leq max\_Vol * x_{ijrl} \quad \forall i,j \in V, r \in R, l \in L \tag{14}$$

$$\sum_{i \in T} x_{isrl} = \sum_{j \in V} x_{sjrl} \quad \forall s \in S, r \in R, l \in L \tag{15}$$

$$t\_w_{isrl} = 0 \quad \forall i \in V, s \in S, r \in R, l \in L \tag{16}$$

$$\sum_{i \in V} x_{ijrl} = \sum_{k \in C \cup T} x_{jkrl} \quad \forall j \in C, r \in R, l \in L \tag{17}$$

$$t\_w_{ijrl} = 0 \quad \forall i \in C, j \in T, r \in R, l \in L \tag{18}$$

$$x_{ijrl} = 0 \quad \forall i,j \in S, r \in R, l \in L \tag{19}$$

$$x_{ijrl} = 0 \quad \forall i \in C, j \in S, r \in R, l \in L \tag{20}$$

$$x_{iirl} = 0 \quad \forall i \in V, r \in R, l \in L \tag{21}$$

Objective function (2) is based on Eq. (1) and minimizes the GHG emissions generated throughout all LSP transport networks. Equations (3) and (4) make sure that exactly one logistics service provider is engaged for the transport of each product. Equations (5) and (6) guarantee that a given logistics service provider can only travel to and from those transshipment point locations that belong to its transport network. Equation (7) ensures that the total weight leaving a supplier is not greater than its supply capacity. Note that the main purpose of Eq. (7) is not to set an upper bound for the number of goods offered by a certain supplier because this quantity will always be sufficient to serve the total demand. Instead, Eq. (7), in combination with Constraints (8) and (9), is for modeling the flow conservation in the transport network. Equation (7) indicates the sources in the transport network, which are the supplier locations, while Eq. (8) indicates the sinks, which are the customer locations. In addition, Eq. (8) assures that the total demand of each customer regarding a specific product is satisfied. Since cargo is only re-consolidated at the transshipment points, Eq. (9) makes sure that the cargo arriving at a certain transshipment point will also leave it. Equations (10) and (11) calculate the total weight/volume transported on an arc as the sum of the individual product weights/volumes. Equation (12) translates the weight of a certain product transported on an arc into the corresponding number of pallets. Equations (13) and (14) limit the total weight and volume transported on an arc and in a vehicle to the maximum vehicle capacity. Since EN-16258 specifies that all empty trips related to the transport services have to be considered, Eq. (15) makes sure that a truck is sent to a supplier from one of the transshipment points of the selected LSP. Those transport operations do not move any products [Eq. (16)]. Equations (17)–(18) are for modelling the delivery trips: Eq. (17) indicates that the truck that visits a certain customer will also leave from

that customer. The leaving trip may either end at another customer or at a transshipment point. If the destination is another customer, the delivery trip will continue until the delivery trip ends at a transshipment point of the engaged LSP. On the trips towards a transshipment point, no cargo is transported [Eq. (18)]. It should be noted that the products may be transported directly from the suppliers to the customers with no transshipment point in between, where the cargo is re-consolidated. Also, it is possible that a vehicle starts at a certain transshipment point to collect products from a certain supplier and then moves these goods to two or more customers before the vehicle ends its tour at the same transshipment point where the vehicle started or at a different one. As will be shown below, carrying out the computational experiments based on CGT concepts requires a huge computational effort—even for games/scenarios with a small number of players. Thus, there are Eqs. (19)–(21), which shorten the time for solving the mathematical problem by limiting the solution space to meaningful routings: there are no transports between two suppliers, no cargo can travel from a customer to a supplier, and there are no transports from a node to itself.

3.2.2 Scenario 2: customer selects supplier

Scenario 2 reflects a situation where several customers have a demand for a certain product and each customer may select one from several suppliers from who the product will be delivered. In contrast to situation 1, there is only one good demanded by the customers and offered by the suppliers. In addition, there is only one LSP network in this scenario, whereas there are as many transport networks in scenario 1 as there are LSPs to select. Similar to scenario 1, the network flow model processes the three factors that are also used in EN-16258 as allocation units, namely distance, mass, and volume.

Let $G = (V, A)$ be again a graph consisting of a set of vertices V and arcs A. V consists of the set of suppliers S, customers C, and transshipment points T. Moreover, there is a set of vehicles/routes R, which allows the LSP to use a certain arc of the transport network more than one time to move cargo from one location to another. Similar to scenario 1, there is an empty trip between the supplier and a transshipment point before the cargo is collected and there is an empty trip from the customer back to one of the transshipment points after the freight has been delivered.

Indices

$h, i, j \in V = S \cup C \cup T$	Nodes representing suppliers, customers, and transship. points
$r \in R$	Vehicles/Routes

Decision variables

$y_{cs} \in \{0;1\}$	Equals 1 if customer c chooses supplier s, and 0 otherwise
$x_{ijr} \in \{0;1\}$	Equals 1 if arc (i, j) is traversed in route r, and 0 otherwise
$s\_w_{cs} \in R^+$	Weight-based supply of customer c by supplier s

$s\_tot_s \in R^+$ Total weight-based supply of supplier s

$t\_w_{ijr} \in R^+$ Transported weight from location i to j in route r

$t\_v_{ijr} \in R^+$ Transported volume from location i to j in route r

Parameters

$dist_{ij} \in R^+$	Distance between location i and j
$d\_w_i \in R^+$	Weight-based demand of customer i
$vol \in R^+$	Volume indicated in kilogram per pallet
$max\_Weight \in R^+$	Maximum weight-based payload
$max\_Vol \in R^+$	Maximum volume-based payload
$FC_{empty} \in R^+$	Vehicle fuel consumption when empty (liters per 100 km)
$FC_{full} \in R^+$	Vehicle fuel consumption when fully loaded (liters per 100 km)
$ECF \in R^+$	Emission conversion factor (2.67 kg CO_2 equivalents/liter diesel)

Objective

$$min \sum_{i,j \in V, r \in R} \left(FC_{empty} * \frac{dist_{ij}}{100} * ECF * x_{ijr} + (FC_{full} - FC_{empty}) * \frac{t\_w_{ijr}}{max\_Weight} * \frac{dist_{ij}}{100} * ECF \right) \quad (22)$$

Constraints

$$\sum_{s \in S} y_{cs} = 1 \quad \forall c \in C \quad (23)$$

$$s\_w_{cs} = y_{cs} * d\_w_c \quad \forall c \in C, s \in S \quad (24)$$

$$\sum_{c \in C} s\_w_{cs} = s\_tot_s \quad \forall s \in S \quad (25)$$

$$\sum_{j \in V, r \in R} t\_w_{ijr} - \sum_{h \in V, r \in R} t\_w_{hir} \leq s\_tot_i \quad \forall i \in S \quad (26)$$

$$\sum_{j \in V, r \in R} t\_w_{ijr} - \sum_{h \in V, r \in R} t\_w_{hir} = -d\_w_i \quad \forall i \in C \quad (27)$$

$$\sum_{j \in V, r \in R} t\_w_{ijr} - \sum_{h \in V, r \in R} t\_w_{hir} = 0 \quad \forall i \in T \quad (28)$$

$$t\_v_{ijr} = t\_w_{ijr}/vol \quad \forall i, j \in V, r \in R \quad (29)$$

$$t\_w_{ijr} \leq max\_Weight * x_{ijr} \quad \forall i, j \in V, r \in R \quad (30)$$

$$t\_v_{ijr} \leq max\_Vol * x_{ijr} \quad \forall i, j \in V, r \in R \tag{31}$$

$$\sum_{i \in T} x_{isr} = \sum_{j \in V} x_{sjr} \quad \forall s \in S, r \in R \tag{32}$$

$$t\_w_{isr} = 0 \quad \forall i \in V, s \in S, r \in R \tag{33}$$

$$\sum_{i \in V} x_{ijr} = \sum_{k \in C \cup T} x_{jkr} \quad \forall j \in C, r \in R \tag{34}$$

$$t\_w_{ijr} = 0 \quad \forall i \in C, j \in T, r \in R \tag{35}$$

$$x_{ijr} = 0 \quad \forall i, j \in S, r \in R \tag{36}$$

$$x_{ijr} = 0 \quad \forall i \in C, j \in S, r \in R \tag{37}$$

$$x_{iir} = 0 \quad \forall i \in V, r \in R \tag{38}$$

Objective function (22) minimizes the GHG emissions while serving all customer requests. Equation (23) makes sure that each customer selects exactly one supplier to serve its request. Equation (24) assigns the corresponding demand of the customer to the selected supplier. Equation (25) computes the total supply of a certain supplier as the sum of the delivery quantities to the single customers. Equations (26)–(28) are the flow conservation constraints: Eq. (26) ensures that the cargo leaving a supplier is not greater than its supply capacity. Similar to scenario 1, the main purpose of Eq. (26) is not to set an upper bound for the number of goods offered by the single suppliers (because the quantity offered will always be sufficient to satisfy the demand) but to indicate the sources in the transport network. Equation (27) guarantees that the demand of all customers is fulfilled. Equation (28) ensures that the cargo that arrives at a transshipment point leaves it again. Equation (29) translates the weight transported in a vehicle into the corresponding number of pallets. Equations (30) and (31) limit the total weight and volume transported in a vehicle to the maximum vehicle capacity. Equation (32) makes sure that a truck is sent from a transshipment point to a supplier before the cargo is collected. Those vehicle movements do not transport any products [Eq. (33)]. Similar to scenario 1, Eqs. (34)–(35) model the delivery trips: Eq. (34) states that a truck that visits a certain customer will also leave from there, where the leaving trip may either end at another customer or at one of the transshipment points. If the destination is another customer, the delivery trip will continue until it ends at a transshipment point. On the trips towards a transshipment point, no cargo is transported [Eq. (35)]. Similar to Scenario 1, the products may be transported directly from the suppliers to the customers with no transshipment point in between.

Also, it is possible that a vehicle starts at a certain transshipment point to collect the products from a certain supplier and then moves these goods to two or more customers before the vehicle ends its tour at the same transshipment point where the vehicle started or at a different one. Finally, Eqs. (36)–(38) allow solving the mathematical problems that come with application of the CGT framework in a reasonable amount of time by limiting the solution space to meaningful routings, analogously to scenario 1; i.e., there are no transports between two suppliers, no cargo can travel from a customer to a supplier, and there are no transports from a node to itself.

3.3 CGT framework for studying the pollution routing game

Our research starts from the point of view that the most meaningful allocation unit is the one that best implements pragmatism, accuracy, fairness, and the GHG minimizing incentive. As all EN-16258 allocation schemes are pragmatic (cf. Kellner and Schneiderbauer 2019), we compare them with respect to accuracy, fairness, and their GHG minimizing incentive in the novel transport scenarios. For doing this, we use concepts of the cooperative game theory.

3.3.1 Aspect 1: accuracy

Accuracy means that an allocation rule distributes GHG emissions according to the polluter-pays principle. Accuracy is important as an inaccurate allocation of emissions increases the risk of taking ineffective measures when trying to cut down transport-related greenhouse gases.

In order to assess the accuracy of the EN-16258 allocation schemes, we follow the methodology suggested by Kellner (2016) and Kellner and Schneiderbauer (2019) and compare the allocation vectors produced by the EN-16258 rules with the outcome when applying the Shapley value (Shapley 1953). This approach allows us to observe if the findings of the prior research projects are also valid in the extended transport scenarios developed in this study. The Shapley value (SV) is a CGT solution concept based on the philosophy that a player should receive a share in a cooperative game that is proportional to her/his average marginal contribution when joining any possible coalition of players (Shapley 1953). In the context of the allocation of GHG to shipments, the SV represents a weighted average of the marginal GHG contributions of the single shipments to all possible coalitions of the other players/shipments. The CGT setting is as follows: There are n shipments among which the total GHG emissions are to be distributed. $N = \{1, 2 \ldots n\}$ is the set of all shipments, with k being the index of the single shipment. S represents one of the $(2^n - 1)$ possible non-empty sub-coalitions in N. Let $ghg(S)$ be the GHG calculated for sub-coalition S and $[ghg(S \cup \{k\}) - ghg(S)]$ the marginal emissions of adding shipment k to S. Then, the Shapley value for shipment k ($shapley_k$) can be computed according to Eq. (39):

$$shapley_k = \sum_{S \subseteq N/\{k\}} \frac{|S|! * (n - |S| - 1)!}{n!} * \left[ghg(S \cup \{k\}) - ghg(S) \right] \qquad (39)$$

The term preceding the marginal GHG emissions when adding shipment k to coalition S is for weighing the latter and for establishing the average: $|S|!$ computes the sequence the set S could have been formed prior to shipment k's addition and $(n–|S|–1)!$ the sequence the remaining shipments can be added. Lastly, it is summarized over all possible sets and averaged by dividing by $n!$. Note that, in the following, the Shapley value refers to the full vector, which indicates the GHG shares allocated to all shipments.

For assessing the accuracy of the EN-16258 allocation rules, we compare the shares of the GHG attributed to the single shipments indicated in percent with the percentage shares that are attributed by the Shapley value. y_k is generally the share of GHG allocated to shipment k, and $y(ar)_k$ is the share that allocation rule ar assigns to k. sv_k is the share that the SV allocates to k. The similarity between the EN-16258 allocation vectors $y(ar)$ and sv is measured with the mean absolute deviation (MAD) and the mean squared deviation (MSD). This allows us to observe if different similarity measures result in the same conclusions. Note that the MSD 'penalizes' greater deviations in the allocation vectors more severely because the single deviations are raised to the power of two, while the MAD penalizes proportionally to the absolute deviation. Thus, the MAD and the MSD will result in different conclusions especially in the cases of outliers, i.e., when the allocated percentage shares of some players differ significantly between the SV and the considered EN-16258 rule.

$$MAD(ar) = \frac{1}{n} \sum_k \left| y(ar)_k - sv_k \right| \quad \forall ar \qquad (40)$$

$$MSD(ar) = \frac{1}{n} \sum_k \left(y(ar)_k - sv_k \right)^2 \quad \forall ar \qquad (41)$$

3.3.2 The characteristic function ghg

The characteristic function ghg, which assigns coalition value $ghg(S)$ to coalition S, holds a central position in this study as it is a prerequisite for computing the Shapley value and as it serves in different ways for assessing the fairness of the EN-16258 allocation rules. Generally, the characteristic function of a game attributes a specific value to any subset $S \subseteq N$. If the game is a profit game, this value indicates how much collective payoff a set of players can gain when forming a coalition; if the game is a cost game—as in the case of the allocation of GHG emissions to shipments—, it represents the minimum costs (GHG) achievable. For scenarios 1 and 2, this implicates that $ghg(S)$ is represented by the GHG minimal solution that allows serving all customer requests in coalition S. Therefore, the objective functions of both models have been formulated to minimize the overall GHG.

Table 2 Overview on the fairness criteria

Criterion	Description
Individual rationality (IR)	For each player k, the allocated amount of GHG y_k does not exceed the stand-alone emissions $ghg(\{k\})$: $y_k \leq ghg(\{k\}), \forall k \in N$
Coalition stability (CS)	No subset S of multiple players receives more GHG than would be the case if the multi-player coalition was served alone: $\sum_{k \in S} y_k \leq ghg(S), \forall S \subseteq N, |S| > 1$
Core performance	The allocation vector is in the Core Γ of the PRG: $$\Gamma(PRG) := \left\{ y \in \mathbb{R}^N \,\middle|\, \sum_{k \in N} y_k = ghg(N) ; \sum_{k \in S} y_k \leq ghg(S), S \subseteq N \right\}$$
Semicore performance	The allocation vector is in the Semicore of the PRG: $y_k \leq ghg(\{k\}), \ \forall k \in N$ $\sum_{i \in N \setminus \{k\}} y_i \leq ghg(N \setminus \{k\}), \forall k \in N$ $\sum_{k \in N} y_k = ghg(N)$
Causation	The rank order of the allocated emissions y_k is identical to the rank order of the shipments' individual emissions $ghg(\{k\})$

3.3.3 Aspect 2: fairness

Besides accuracy, it is important that an allocation scheme is perceived as being fair. If an allocation rule is perceived as unfair, the risk increases that the partners of the logistics network stop the cooperation and that the overall emissions raise as there are many single shipments that are moved in separated transport operations.

For assessing the performance of the EN-16258 allocation schemes with respect to fairness, we observe in how many PRG instances, the different rules are in line with a set of CGT fairness criteria. The criteria used in this study are inspired by prior studies that presented criteria to evaluate allocation methods in joint transportation (e.g., Fishburn and Pollak 1987; Flisberg et al. 2015; Kellner and Schneiderbauer 2019; Naber et al. 2015; Young 1994; Zhu et al. 2014). The selection of the fairness criteria in this study is aligned to the objective to identify an allocation scheme that is reasonable to any player and to promote the stability of the cooperation. Table 2 summarizes the criteria used.

Individual Rationality (*IR*) indicates a situation where no single player receives a share of GHG greater than its stand-alone emissions. *Coalition Stability* (*CS*) indicates that there is no sub-set of several players of the grand coalition that receives more GHG than it would be the case when the coalition is served alone. Note that, in this research, CS refers exclusively to the multi-player coalitions, i.e., to all sub-sets of players of the grand coalition consisting of more than one player, while IR refers to the single-player 'coalitions.' This allows us to study the performance of the EN-16258 allocation vectors for two distinct, not overlapping sets of sub-coalitions. Moreover, if we included IR in CS, then the analysis concerning the Core (see below) would not be necessary as the Core performance would be the same as CS because all EN-16258 rules are designed in such a way that they guarantee efficiency. The Core combines IR, CS, and efficiency, where efficiency states that the allocation vector exactly splits the total GHG, i.e., the sum of the GHG allocated to the single players adds up to the GHG of the grand coalition. *Core performance* verifies whether the allocation vector is in the Core Γ of the game. If an allocation

vector is in the Core, then it is guaranteed that no sub-set of players has an incentive to stop cooperating as no coalition has a $ghg(S)$ value smaller than the sum of its members' GHG payoffs. As it might be hard for the EN-16258 allocation rules to produce allocation vectors that are completely in the Core of the game, we analyze the allocation rules additionally with respect to their *Semicore performance*. The Semicore (Young 1994) is a relaxed version of the Core and based on some key values of the characteristic function, namely the $ghg(S)$ values of the single player coalitions and their complement coalitions. And *Causation* indicates a situation where the rank order of the allocated emissions is identical to the rank order of the shipments' individual emissions. Details on the exact calculations of these fairness measures are provided, together with illustrative examples, in Sect. 4.

3.3.4 Aspect 3: GHG minimizing incentive

Finally, we observe the incentive power of the EN-16258 allocation schemes to opt for the GHG minimal way of running a road freight transport network. For analyzing this aspect, the two decision situations presented in Sect. 3.1/3.2 are studied.

Situation 1: supplier selects carrier In this situation, there are several customers ordering distinct products at the corresponding suppliers and each supplier may nominate one from several LSPs to move all of its shipments to the customers. In order to study the GHG minimizing incentive of the EN-16258 allocation rules, we proceed as follows: we firstly solve the presented optimization model to optimality and note down which ones from the available LSPs are selected by the single suppliers in the GHG minimal network configuration. Then, we apply the different EN-16258 allocation rules to allocate the GHG to the suppliers. For the allocation step, we follow the VOS concept specified in EN-16258 and define the vehicle operating system as all transport operations carried out by a certain LSP to move the single shipments from their origins to their destinations. In doing so, we assume that the overall GHG emissions of a given transport network are calculated by the LSP who is operating this network. In the next step, we make supplier #1 deviating from the GHG minimal network configuration by replacing consecutively the LSP selected by supplier #1 with each one of the other LSPs. Concerning the other suppliers, we analyze the case where all other suppliers do not change their initial selection and the case where all other suppliers are also allowed to change their behavior in response to the change of supplier #1. Then, the optimization models are solved again. Finally, we verify whether there are EN-16258 allocation rules that assign less GHG to supplier #1 after an LSP has been selected that is sub-optimal from a total GHG point of view. Details on the calculations are presented in Sect. 4.

Situation 2: customer selects supplier In this situation, there are several customers with a demand for a certain product and each customer may choose a certain supplier from who this product will be sourced. In this setting, we proceed as follows: firstly, the presented optimization model is solved to optimality and we note down which ones from the available suppliers are chosen by the single customers in the optimal configuration. Then, we apply the different EN-16258 allocation

schemes to distribute the GHG among the customers. For the allocation step, we follow again the VOS concept and define the vehicle operating system as all transport operations carried out by the LSP operating the transport network. Note that, in situation 2, there is only one LSP serving all customer requests. Then, we replace consecutively the supplier selected by customer #1 with each one of the other suppliers. Concerning the other customers, we analyze the case where all other customers do not deviate from the GHG minimal network configuration and the case where all other customers are also allowed to change their behavior in response to the change of customer #1. Then, we solve the optimization model to optimality again. Lastly, we verify if there are allocation schemes assigning less GHG to customer #1 when opting for a supplier that is sub-optimal from a total GHG perspective.

4 Numerical experiments

4.1 Setup of the numerical study

In this research, we study the performance of the EN-16258 allocation rules in a total of 100 PRGs; for each transport scenario, 50 PRG instances are created. The instances differ in the number and geographical locations of the suppliers, customers, and carrier transshipment points, in the vehicles that move the goods, and in the shipment sizes in terms of weight and volume. The distances between the different locations are represented by Euclidean distances. Concerning the distances used for the allocation (Table 1), we also use Euclidean distances, namely those between the single suppliers and the single customers. This corresponds to the shortest feasible distance and approximates the great circle distance as the geographical area of the games studied does not cover several hundred kilometers.

As a great share of our analyses is based on the characteristic functions of the PRGs, an extensive computational study is required. To be precise, for each PRG, we need to determine the GHG minimal network configuration for each one of the $(2^n - 1)$ possible sub-sets of the grand coalition. In addition, for studying the GHG minimizing incentive, each PRG is solved to optimality for each possible deviation from the GHG minimal solution. Thus, the results presented below are based on the optimal solutions of several hundred mixed-integer optimization programs.

As for the computational resources, the mixed-integer optimization problems are solved using Gurobi 9.1 with the default parameter settings and a flow control organizing the sequence of the calculations coded in Python. All calculations are carried out on a couple of Amazon EC2 virtual computers, each equipped with 32 CPU Cores and 256 GB RAM, working in parallel. The Shapley formula has been coded in MATLAB R2019b.

4.1.1 Situation 1: supplier selects carrier

For scenario 1, we simulate 25 PRG instances with four suppliers and 25 instances with three suppliers. The differing number of suppliers allows us to observe if this variable affects the outcome and to estimate (at least crudely) to what extent

the results may be extrapolated to a higher number of players. Note that, in situation 1, the suppliers are the players in these games among which the total GHG are to be distributed. In each PRG instance, there are nine customers. The suppliers and the customers are located at random positions in a coordinate system ranging for the *x*–*y*-coordinate pairs from − 100 to 100. Each one of the suppliers can choose one out of two carriers. Thus, in the case of three suppliers, there are $2^3 = 8$ possible supplier-carrier combinations and the characteristic functions are made up of 7 $ghg(S)$ values; in the case of 4 suppliers, there are $2^4 = 16$ possible supplier-carrier combinations and the characteristic functions are made up of 15 $ghg(S)$ values. Each carrier operates three transshipment points. As scenario 1 is a network flow setting, which is typical for long-distance transportation, the trucks are medium- and high-volume heavy goods vehicles. For 25 PRGs, we use a medium-size truck and for the other 25 PRGs a high-volume truck. This allows us to study the effect of the vehicle type on the outcome and to estimate the generalizability of our findings. The high-volume truck has a maximum weight-based payload capacity of 25 tons and a volume-based capacity of 34 pallets. The fuel consumption patterns of the trucks are taken from Kranke et al. (2011): $FC_{full} = 31.7$ l/100 km and $FC_{empty} = 21.5$ l/100 km. The medium-size truck has a maximum weight-based payload capacity of 17 tons and a volume-based capacity of 20 pallets, $FC_{full} = 30.3$ l/100 km, and $FC_{empty} = 19.7$ l/100 km. In order to achieve a good mix in the PRG instances created, we use for the first 25 instances the high-volume truck, and for the instances 26–50 the medium-size truck. For all PRGs where the index ends with the numbers 1, 2, 3, 4, or 5 (i.e., PRGs 1–5, 11–15, 21–25, 31–35, 41–45) we simulate four suppliers; and for all PRGs where the index ends with the numbers 6, 7, 8, 9, or 0 (i.e., PRGs 6–10, 16–20, 26–30, 36–40, 46–50) we simulate three suppliers. The shipment sizes are randomly generated figures following a normal distribution with parameters for the mean and the standard deviation taken from the shipment dataset of an existing major manufacturer of consumer goods. The mean shipment size is 1000 kg for mass and 550 kg/palette for the volume. The standard deviations are 1000 kg for mass and 190 kg/palette for volume. The randomly generated figures consider the fact that the minimum and the maximum mass-based shipment sizes are 50 kg and around 15,000 kg, respectively, and the volume-based shipment sizes are between 200 kg/palette and 900 kg/palette. When randomly generating the shipment sizes, the draws for the mass (in kg) and the volume (in kg/pallet) per shipment are independent of each other. We opted for independent drawings since the dataset used does not indicate a strong relationship between the mass and the volume of the single shipments [the correlation coefficient for mass (kg) and volume (kg/pallet) is 0.06], which may be explained by the great number of products included in the dataset. That is, there are high-mass-low-volume but also low-mass-high-volume shipments. Note that the number of pallets tends to be greater when the mass (in kg) is greater since the number of pallets is determined by dividing the mass by the volume (in kg/pallet).

Table 3 Overview on the setting of the PRGs studied

Scenario	Setting
Scenario 1 Supplier selects carrier (Player = Supplier)	– Suppliers: 3 or 4; locations: randomly generated coordinate pairs[a]
	– Customers: 9; locations: randomly generated coordinate pairs[a]
	– LSPs: 2 with 3 transshipment points; locations: fixed points
	– Vehicles: high-volume (max_Weight = 25 tons, max_Vol = 34 pallets) and medium-size (max_Weight = 17 tons, max_Vol = 20 pallets) trucks
	– Shipment sizes: randomly generated figures following a normal distribution
Scenario 2 Customer selects supplier (Player = Customer)	– Suppliers: 4; locations: randomly generated coordinate pairs[a]
	– Customers: 6 or 9; locations: randomly generated coordinate pairs[a]
	– LSPs: 1 with 4 transshipment points; locations: fixed points
	– Vehicles: high-volume (max_Weight = 25 tons, max_Vol = 34 pallets) and medium-size (max_Weight = 17 tons, max_Vol = 20 pallets) trucks
	– Shipment sizes: randomly generated figures following a normal distribution

[a] x–y-values between -100 and 100 (uniformly distributed)

4.1.2 Situation 2: customer selects supplier

For scenario 2, there are also 50 PRG instances. This time, the players are not the suppliers but the consignees, among which the total GHG are to be distributed. 25 PRGs are simulated with nine customers and 25 PRGs are run with six customers. In each PRG instance, the nine/six customers have to choose one out of four suppliers from whom they order the product desired. There is one LSP operating four transshipment points. As there are nine/six players and four suppliers, there are $4^9 = 262{,}144$ and $4^6 = 4096$ possible customer–supplier combinations, respectively. The characteristic functions consist of 511 and 64 $ghg(S)$ values, respectively. Similar to Scenario 1, we assume for 25 PRG instances a high-volume heavy goods vehicle, and for the other 25 PRGs a medium-size truck. These vehicles have the same characteristics as the vehicles in Scenario 1. The mix in the number of players and the vehicles used is in line with scenario 1, i.e., we use for the first 25 PRG instances the high-volume truck, and for the instances 26 to 50 the medium-size vehicle. For all PRGs where the index ends with the numbers 1, 2, 3, 4, or 5 (see above) we simulate nine customers; and for all PRGs where the index ends with the numbers 6, 7, 8, 9, or 0 we simulate six customers. In this scenario, we assume shipment sizes of the customer orders that are a multiple (between 5 and 10) of those in situation 1. Table 3 provides an overview on the setup of the PRGs studied.

4.2 Results of the numerical study

4.2.1 Aspect 1: accuracy

For assessing the accuracy of the EN-16258 allocation rules, we compare the generated allocation vectors with the one that results when applying the Shapley value. The deviation of the EN-16258 allocation schemes from the SV is

Table 4 Means of the MAD and MSD of the EN-16258 GHG allocation rules when compared with the Shapley value (values in percentage points)

Scenario	# Players/Vehicle type	Ton MAD ‖ MSD	Volume MAD ‖ MSD	Kilometer MAD ‖ MSD	Ton-Kilom. MAD ‖ MSD	Vol.-Kilom. MAD ‖ MSD
Scenario 1 (50 PRGs)	4 Players (25 PRGs)	4.8 ‖ 0.4	6.2 ‖ 0.6	3.9 ‖ 0.3	5.3 ‖ 0.4	7.0 ‖ 0.8
	3 Players (25 PRGs)	4.7 ‖ 0.4	7.3 ‖ 0.9	5.0 ‖ 0.4	5.2 ‖ 0.4	6.7 ‖ 0.7
	High-volume (25 PRGs)	3.7 ‖ 0.2	8.1 ‖ 1.0	3.5 ‖ 0.2	4.7 ‖ 0.3	8.8 ‖ 1.1
	Medium-size (25 PRGs)	5.9 ‖ 0.5	5.5 ‖ 0.5	5.5 ‖ 0.5	5.7 ‖ 0.5	5.1 ‖ 0.4
Scenario 2 (50 PRGs)	9 Players (25 PRGs)	3.9 ‖ 0.2	3.9 ‖ 0.2	6.3 ‖ 0.7	4.3 ‖ 0.3	4.3 ‖ 0.3
	6 Players (25 PRGs)	8.5 ‖ 1.3	8.5 ‖ 1.3	9.3 ‖ 1.4	8.3 ‖ 1.3	8.3 ‖ 1.3
	High-volume (25 PRGs)	6.6 ‖ 0.9	6.6 ‖ 0.9	6.0 ‖ 0.6	7.1 ‖ 1.1	7.1 ‖ 1.1
	Medium-size (25 PRGs)	5.8 ‖ 0.6	5.8 ‖ 0.6	9.3 ‖ 1.4	5.7 ‖ 0.6	5.7 ‖ 0.6
Scenario 1 (50 PRGs)		4.8 ‖ 0.4	6.8 ‖ 0.7	4.5 ‖ 0.3	5.2 ‖ 0.4	6.9 ‖ 0.7
Scenario 2 (50 PRGs)		6.2 ‖ 0.8	6.2 ‖ 0.8	7.8 ‖ 1.0	6.3 ‖ 0.8	6.3 ‖ 0.8

measured with the mean absolute and the mean squared deviation of the allocated percentage shares. Table 4 shows summary statistics of this comparison, indicating the mean MAD and the mean MSD per scenario. The volume in columns 4 and 7 is measured in pallets.

The calculation of the values 4.8 and 0.4 in Table 4 for the mean MAD and the mean MSD in the case of Scenario 1, 4 Players, 'Ton' allocation scheme, for instance, is done as follows: first, we compute, for each PRG separately, the percentage shares of the overall GHG that are assigned to the four players when using the ton-based allocation scheme and when using the SV. Then, we determine the mean absolute and the mean squared deviations of both allocation vectors. Suppose, e.g., that 'Ton' assigns, in a given PRG, the following GHG shares to the four players: 20% Player 1, 30% Player 2, 40% Player 3, and 10% Players 4. If, for the same PRG, the SV assigns 10% to Player 1, 20% to Player 2, 50% to Player 3, and 20% to Players 4, then the MAD for this PRG is 0.1 $(=(|0.2–0.1|+|0.3–0.2|+|0.4–0.5|+|0.1–0.2|)/4)$ and the MSD is 0.01 $(=((0.2–0.1)^2+(0.3–0.2)^2+(0.4–0.5)^2+(0.1–0.2)^2)/4)$. The values in Table 4 are the means of these calculations over all PRGs that belong to a certain scenario-player/-vehicle configuration. This means that in the case of Scenario 1 and 4 Players, the allocation vectors based on 'Ton' are on average closer to the allocation vectors generated by the SV than the allocation vectors based on 'Volume' (4.8% vs. 6.2% and 0.4% vs. 0.6%).

Table 4 shows that the relative performance of the different allocation rules, in terms of small MAD values, differs as a function of the scenario, the number of players, and the vehicle used. Thus, a detailed analysis is required. As many figures in Table 4 are in a narrow range, we check the statistical significance of one MAD being greater than another using the pairwise Wilcoxon rank-sum test. A given MAD is classified 'significantly greater' than another if the corresponding *p*-value is below 5%. In the following, we will focus on those results that are statistically significant.

For Scenario 1, the smallest mean MAD (4.5) is realized when 'Kilometer' is used to allocate the overall GHG emissions to the players. This result confirms the observations made by Kellner (2016) and Kellner and Schneiderbauer (2019). According to the statistical test, the MAD of 'Volume' and 'Volume-Kilometer' are significantly greater than the MAD of 'Kilometer.' Table 4 shows that, when high-volume vehicles are used, then the Kilometer-based allocation scheme has a lower mean MAD than all the other rules. This observation is statistically significant when 'Kilometer' is compared with 'Volume' and 'Volume-Kilometer.' On the other hand, when the medium-size vehicle is used to move the goods, then the vehicle capacity is more decisive for the routing of the vehicles and, finally, for the GHG generated. This explains why 'Volume' and 'Volume-Kilometer' perform at least as well as the other allocation rules when the medium-size vehicle is used. In summary, the observations form scenario 1 are quite in line with the results reported in prior research studies (put it simply: 'the Kilometer-based rule is a good choice'). However, in this study, we do not find the same dominance of 'Kilometer' as it was found in the previous studies. We argue that this is especially due to the fact that the previous

studies considered the physical and the route-planning effect of the single shipments on GHG emissions, whereas this study adds another aspect, which is the possibility to use another carrier to move the goods.

For Scenario 2, interestingly, the Kilometer-based rule performs on average worse than the other allocation schemes (7.8% vs. 6.2%), even if this observation is statistically not significant at a *p*-value of 5%. On the other hand, in the case of nine players, 'Kilometer' realizes a mean MAD that is significantly greater than the mean MAD of all the other allocation rules. A closer look at the vehicles used shows that, when the medium-size vehicle is used, all allocation rules perform better than 'Kilometer.' There are especially two aspects that explain the bad performance of the Kilometer-based allocation rule in scenario 2. First, the results show that 'Kilometer' performs particularly bad when there are more players and the vehicle capacity is reduced. This indicates that the capacity of the vehicles and the degree to which the single shipments use the vehicle capacities are especially decisive for the GHG generated because this affects the routing of the trucks. In addition, in scenario 2, the distance travelled is less relevant for GHG emissions because the customers can switch the supplier (i.e., the corresponding location) in order to minimize GHG. This means that the distance that needs to be travelled is not determined in advance because the source can be changed. This is an important difference to scenario 1, and also to the models studied by Kellner (2016) and Kellner and Schneiderbauer (2019). The second aspect that explains the bad performance of 'Kilometer' in scenario 2 is the way the benchmark, i.e., the Shapley value, is calculated. To be precise, for the calculation of the characteristic function, which serves as the input of the SV, numerous optimal network configurations are determined. As there are some configurations where the customers select suppliers that are different to those
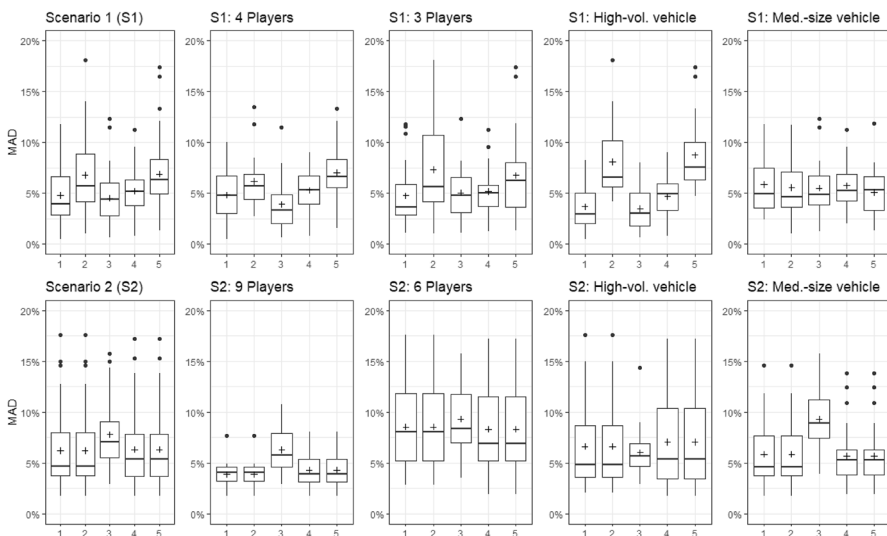
Fig. 2 Summary statistics for the MAD of the percentage shares allocated by the EN-16258 rules from the Shapley value (*x*-axis: 1 = Ton, 2 = Vol., 3 = Kilometer, 4 = Ton-Kilom., 5 = Vol.-Kilom.)

selected for the grand coalition, the distance used for the allocation might not be representative for all sub-coalitions. Based on these findings, we argue that the similarity of the allocation vector based on 'Kilometer' compared to the Shapley value largely depends on the definition of the term 'shipment' or 'transport service.' When following the definition of Kellner and Schneiderbauer (2019), who see '… a transport service as a request to move a certain object with a certain mass and a certain volume from one location to another,' then the allocation vector based on 'Kilometer' will be closer to the SV because, then, the origin and the destination locations are fixed and the distances between these locations cannot change from one sub-coalition to another. These distances will be highly decisive for the overall GHG of the transport operations—not only for the grand coalition. On the other hand, when the origin and/or the destination locations are not specified in advance, then the distance is less relevant for the overall GHG because the origin/destination can be changed in order to minimize the overall GHG.

Table 4 summarizes our observations concerning the deviations of the percentage shares allocated by the EN-16258 rules from the SV using the means of the MAD and MSD. Figure 2 presents more statistical details for the MAD across the investigated PRGs. The upper and the lower series of boxplots show statistics for scenario 1 and 2, respectively. In analogy to Table 4, we indicate statistics for the MAD for the two scenarios in total (leftmost plots), and then, from left to right, we go more into the details by only showing the picture for a given number of players or a certain vehicle. The boxplots indicate, for each sample and allocation rule separately, the 25th, 50th, and 75th percentiles. In addition, the upper (lower) whisker extends

Table 5 Performance of the EN-16258 allocation schemes w.r.t. the CGT fairness criteria

Scenario		Ton	Volume	Kilometer	Ton-Kilom.	Vol.-Kilom.	SV
Scenario 1 (50 PRGs)	IR	98% (99%)	89% (97%)	96% (99%)	94% (98%)	83% (95%)	100% (100%)
	CS	66% (93%)	47% (89%)	62% (92%)	57% (91%)	57% (91%)	100% (100%)
	Core perf.	66% (95%)	47% (92%)	62% (94%)	57% (94%)	57% (92%)	100% (100%)
	Semicore	68% (95%)	49% (90%)	62% (93%)	57% (93%)	57% (90%)	100% (100%)
	Causation	41%	47%	39%	45%	55%	68%
Scenario 2 (50 PRGs)	IR	4% (68%)	4% (68%)	20% (72%)	4% (74%)	4% (74%)	74% (92%)
	CS	0% (66%)	0% (66%)	0% (64%)	0% (65%)	0% (65%)	2% (85%)
	Core perf.	0% (66%)	0% (66%)	0% (65%)	0% (65%)	0% (65%)	2% (85%)
	Semicore	0% (63%)	0% (63%)	0% (64%)	0% (63%)	0% (63%)	16% (82%)
	Causation	23%	23%	24%	30%	30%	42%
Total (100 PRGs)	IR	49% (83%)	45% (82%)	57% (85%)	47% (85%)	42% (84%)	87% (96%)
	CS	32% (79%)	23% (78%)	30% (78%)	28% (78%)	28% (77%)	49% (92%)
	Core perf.	32% (80%)	23% (79%)	30% (79%)	28% (79%)	28% (78%)	49% (92%)
	Semicore	33% (79%)	24% (76%)	30% (78%)	28% (77%)	28% (76%)	57% (91%)
	Causation	32%	35%	31%	37%	42%	54%

from the hinge to the largest (smallest) value no further than (at most) 1.5*IQR from (of) the hinge. The IQR is the interquartile range, i.e., the distance between the first and third quartiles. Data beyond the end of the whiskers are considered as outliers and plotted individually. The '+' symbol indicates the mean (cf. Table 4).

When using the MSD for the comparison of the performance of the single allocation rules, our findings do not change a lot, i.e., in almost all rows in Table 4 the ranking order of the MSD is the same as it is for the MAD.

4.2.2 Aspect 2: fairness

Table 5 summarizes the performance of the EN-16258 allocation rules with respect to the CGT fairness criteria introduced in Sect. 3.3.3. The rightmost column shows the performance of the Shapley value, which serves as the CGT benchmark. Concerning IR, CS, the Core, and the Semicore criterion, the numbers outside the brackets indicate the percentage shares of the PRGs where the different fairness criteria are completely met. The numbers inside the brackets show the average percentage shares of the rationality constraints that have been met by the single rules across all PRGs. These numbers indicate the percentage shares of the coalitions, across all PRGs, that do not have an incentive to stop the cooperation because they receive GHG allocated that are greater than their stand-alone emissions. If, for instance, there are four players in a given PRG, then the characteristic function of this game consists of 15 elements. If one of the single player coalitions receives more GHG allocated than is the corresponding $ghg(S)$ value and the other 14 coalitions receive less GHG allocated, then the numbers in brackets would be $1–1/4 = 75\%$ for IR, $1–0/11 = 100\%$ for CS, $1–1/15 = 93\%$ for Core performance, and $1–1/8 = 87.5\%$ for Semicore for this game. The numbers outside the brackets would be 0% for IR, 100% for CS, 0% for Core performance, and 0% for Semicore since CS is completely met but the other three criteria are not completely met, i.e., there is at least one sub-coalition that has an incentive to stop the cooperation. Or put it less technically: the numbers outside the brackets indicate the share of the PRGs where all sub-coalitions are 'happy,' whereas the values inside the brackets indicate the average share of the 'happy' sub-coalitions per PRG. In this context, a sub-coalition is called 'happy' if it receives less GHG allocated than are its stand-alone emissions. The figures in Table 5 may be interpreted as an indicator for the stability of the transport cooperation after the GHG have been allocated. At this point, we want to reiterate that, in this research, CS refers exclusively to all multi-player coalitions, i.e., it does not include the single-player coalitions (IR). If we included IR in CS, then the analysis concerning Core performance would not be necessary as Core performance would be the same as CS because all EN-16258 rules are designed in such a way that they guarantee efficiency. Concerning Causation, the numbers in the table indicate the average percentage shares of the players where the rank order of the allocated emissions y_k is identical to the rank order of the shipments' individual emissions $ghg(\{k\})$. Consider, for instance, a PRG with four players and the shipments' individual emissions are $ghg(\{1\}) = 10$, $ghg(\{2\}) = 20$, $ghg(\{3\}) = 30$, and $ghg(\{4\}) = 40$. If the allocated emissions are $y_1 = 5$, $y_2 = 15$, $y_3 = 10$, and $y_4 = 20$, then
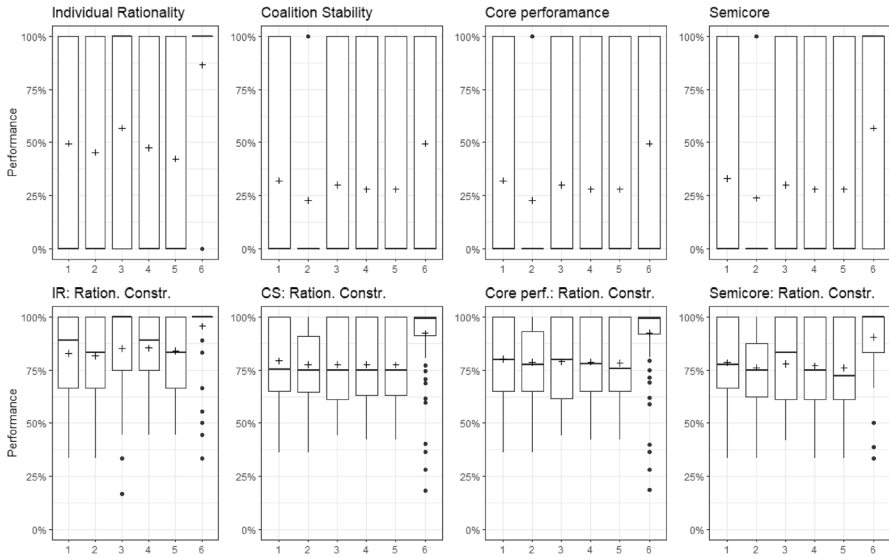
Fig. 3 Summary statistics of the allocation rules' performances w.r.t. IR, CS, Core, and Semicore across all 100 PRGs (x-axis: 1 = Ton, 2 = Vol., 3 = Kilometer, 4 = Ton-Kilom., 5 = Vol.-Kilom., 6 = SV)

the percentage for Causation for this PRG and allocation rule would be 50% since two players (player 1 and 4) have the same rank (player 1 has the lowest and player 4 has the highest individual and allocated emissions), whereas the other two players have changed the rank. That is, for Causation, not the complete rank order of all players is relevant but the individual ranks of the single shipments. Note that the sets of the shipments' 'predecessors' are not considered for the measurement of Causation, only the shipments' individual ranks are relevant. The numbers in Table 5 are the means of this calculation across all (scenario 1/2) PRGs.

Concerning *Individual Rationality*, the allocation rule based on kilometers achieved the best result across all PRGs among the EN-16258 allocation rules. Only the SV achieved a better score. In 57 games, 'Kilometer' met this criterion perfectly. On average, across all 100 PRGs, 85% of the IR rationality constraints are fulfilled when using the Kilometer-based allocation rule, i.e., 85% of all single player coalitions, on average, do not have an incentive to stop the transport cooperation (Table 5, scenario 'Total,' criterion 'IR,' allocation rule 'Kilometer:' value in brackets). The pairwise Wilcoxon rank-sum test indicates that, for a *p*-value of 5%, the 57% of 'Kilometer' is significantly greater than the 42% of 'Vol.-Kilom.'. Table 5 also shows that the relatively good overall performance of 'Kilometer' is especially due to its relatively good performance in scenario 2, where 'Kilometer' achieves a score of 20%, whereas the other EN-16258 rules do not reach 5%.

Table 5 shows that there are—with the exception of the comparatively good score of 'Kilometer' at IR and the SV's overall good performance—no situations where a certain allocation rule excels in a positive or negative manner; i.e., the performances of the EN-16258 allocation rules do not differ significantly at *Coalition Stability*, *Core performance*, *Semicore performance*, and *Causation*. The

statistical rank-sum test, which has been applied to all rows of Table 5, confirms that there is no combination of allocation rules where one percentage share is significantly greater than another. Apart from that, Table 5 shows that there are great differences in the percentage shares when comparing the results of scenario 1 and 2. While most of the percentage scores in scenario 1 are above 50%, the single allocation rules show very bad scores at the single fairness criteria in scenario 2. In particular, the values of 0% at CS, Core performance, and Semicore performance indicate that, in each game, there is at least one coalition that has an incentive to stop the cooperation because it can realize lower GHG emissions when not participating in the grand coalition. This finding indicates that none of the EN-16258 allocation rules is better than the others for guaranteeing the overall stability of the transport cooperation. When comparing the results of this study with observations made in prior research projects, we can confirm the findings of the previous research. To be precise, also in the scenarios studied by Kellner and Schneiderbauer (2019), there is no EN-16258 rule achieving significantly better results than the other rules with respect to CS, Core performance, and Semicore performance. Also, in the prior research, 'Kilometer' showed better results at IR than the other allocation schemes.

Table 5 used the means to aggregate the allocation rules' performances concerning the aspect 'fairness' across multiple PRGs. Figure 3 provides more statistical details for the allocation rules' performances concerning IR, CS, Core, and Semicore across the two scenarios [this refers to the last block in Table 5, named 'Total (100 PRGs)']. The boxplots are created analogously to those in Fig. 2, showing, e.g., the 25th, 50th, and 75th percentiles. The upper series presents the boxplots for the numbers outside the brackets in Table 5 and the lower series shows the boxplots for the numbers inside the brackets.

4.2.3 Aspect 3: GHG minimizing incentive

Aspect 3 refers to the incentive power of the EN-16258 allocation units to opt for the GHG minimal way of running a transport network. Table 6 shows in percentage values how often the different allocation schemes incentivize the focal players in our numerical study to act in an environmentally friendly manner, i.e., how often the allocation schemes allocate the lowest amount of GHG to supplier #1/customer #1 when he chooses the GHG minimal network configuration, and allocate more than in the GHG minimal situation when he deviates from this configuration. For each scenario, two cases are studied: In case 1, only supplier #1/customer #1 changes the initially selected carrier/supplier and all other suppliers/customers do not change their behavior, i.e., they do not deviate from the GHG minimal network configuration. In case 2, the other suppliers/customers are also allowed to change their behavior in response to the change of supplier #1/customer #1, where the objective of this joint deviation is to minimize the overall GHG as far as possible after the change in behavior of supplier #1/customer #1. Note that we refer to the deviation of the other players as 'joint deviation.' The idea behind analyzing both cases where the other players will/will not change their behavior is for studying the corresponding sensitivities since, in practice, both situations can occur. The single steps of this analysis are as follows: (1) we

Table 6 GHG minimizing incentive of the EN-16258 allocation rules (perc. shares indicating how often the allocation rules incentivize the players to opt for the GHG minimal network configuration)

Scenario	Other suppliers/customers	Ton (%)	Volume (%)	Kilometer (%)	Ton-Kilom. (%)	Vol.-Kilom. (%)
Scenario 1 (50 PRGs)	Do not change behavior	100.0	97.9	97.9	97.9	97.9
	Can change behavior	100.0	100.0	100.0	100.0	100.0
Scenario 2 (50 PRGs)	Do not change behavior	100.0	100.0	64.0	64.0	64.0
	Can change behavior	100.0	100.0	60.0	58.0	58.0

determine, for a given PRG, the GHG minimal solution by solving the corresponding optimization model introduced in Sect. 3.2. (2) Based on this solution, we allocate the overall GHG to the single players using the EN-16258 rules. Also, we note down the carriers selected by the different suppliers (scenario 1)/the suppliers selected by the different customers (scenario 2). (3) Now we make player #1 change its behavior. If, e.g., supplier #1 opted in scenario 1 for carrier 1 in the GHG minimal configuration, then we set her/his selection to carrier 2. This behavior change is added as a constraint to the optimization model. If, in the case of scenario 2, customer #1 initially opted for supplier 1, then we set her/his selection at first to supplier 2 and add this preselection to the optimization model. Since customer #1 can select one out of four suppliers, we next preselect supplier 3 and finally supplier 4. Concerning the behavior of the other players, no additional constraints are added to the optimization model if we assume that the other players will change their behavior as a response to the change in behavior of player #1 (joint deviation) to minimize the overall GHG as far as possible. In contrast, if we assume that the other players will not change their behavior, then we add the selection of the other players from the initial situation as constraints to the model. (4) After adding all constraints representing the behavior of the players to the optimization model, this is solved again, i.e., the overall GHG are minimized. (5) Finally, the overall GHG are allocated to the players based on the new solution. Thus, we can observe if player #1 receives less GHG allocated when opting for a sub-optimal solution.

Table 6 shows that all EN-16258 allocation rules incorporate the incentive to behave environmentally friendly, i.e., in most of the PRGs studied, the focal supplier/customer receives more GHG attributed when deviating from the GHG minimal network configuration. Table 6 also indicates that, across all PRGs, the allocation units 'Ton' and 'Volume' incentivize the focal players most often (in almost all cases) to act in an environmentally friendly manner. At this point, it should be noted that, in scenario 2, the percentage scores for 'Ton' and 'Volume' must equal 100% as the shipment weights and volumes do not change, and the routing of the vehicles is irrelevant for the GHG allocated when using 'Ton' and 'Volume' as the allocation unit. In addition, in scenario 2, all shipments use the same carrier network, i.e., the same VOS, as there is only one LSP in this setting. In all other situations, the percentage scores are not directly explicable. This includes the scores for 'Ton' and 'Volume' in scenario 1 because, in this scenario, there are two carriers where each carrier distributes the GHG generated in its transport network among the players making use of its service. Thus, in scenario 1, situations may occur where a supplier opts for another carrier and, in the 'new' transport network, he gets allocated less emissions than in the initially selected transport/carrier network.

Interestingly, in scenario 1, all allocation methods realize very high percentage scores, close to 100%, whereas in scenario 2, the rules based on distances achieve percentage values of around 60%. Table 7 refines the results of Table 6 by focusing on the number of players and the sizes of the transport units.

Table 7 indicates that the number of players does not affect the performance of the single allocation rules with regard to the GHG minimizing incentive, neither in scenario 1 nor in scenario 2. In contrast, for scenario 2, the pairwise rank-sum test detects a significant decrease in these percentage shares when the high-volume

Table 7 GHG minimizing incentive of the EN-16258 allocation rules: detailed results (perc. shares indicating how often the rules incentivize to opt for the GHG minimal network configuration)

Scenario	# Players/vehicle type	Ton (%)	Volume (%)	Kilometer (%)	Ton-Kilom. (%)	Vol.-Kilom. (%)
Scenario 1 (50 PRGs)	4 Players (25 PRGs)	100.0	100.0	95.5	95.5	100.0
	3 Players (25 PRGs)	100.0	96.0	100.0	100.0	96.0
	High-volume (25 PRGs)	100.0	95.7	100.0	100.0	95.7
	Medium-size (25 PRGs)	100.0	100.0	95.8	95.8	100.0
Scenario 2 (50 PRGs)	9 Players (25 PRGs)	100.0	100.0	60.0	56.0	56.0
	6 Players (25 PRGs)	100.0	100.0	60.0	60.0	60.0
	High-volume (25 PRGs)	100.0	100.0	73.9	73.9	73.9
	Medium-size (25 PRGs)	100.0	100.0	48.1	44.4	44.4

Table 8 Additional GHG allocated by the EN-16258 allocation rules when deviating from the GHG minimal network configuration (Case 1: Other suppliers/customers do not change their behavior; Case 2: Other suppliers/customers can change their behavior)

Scenario	# Players/vehicle	Ton	Volume	Kilometer	Ton-Kilom.	Vol.-Kilom.
		Case 1 ‖ Case 2	Case 1 ‖ Case 2	Case 1 ‖ Case 2	Case 1 ‖ Case 2	Case 1 ‖ Case 2
Scenario 1 (50 PRGs)	4 Players	93% ‖ 6%	121% ‖ 6%	115% ‖ 6%	114% ‖ 6%	146% ‖ 6%
	3 Players	76% ‖ 6%	75% ‖ 6%	86% ‖ 6%	86% ‖ 6%	85% ‖ 6%
	High-volume	95% ‖ 7%	103% ‖ 7%	116% ‖ 7%	110% ‖ 7%	123% ‖ 7%
	Medium-size	74% ‖ 4%	90% ‖ 4%	84% ‖ 4%	88% ‖ 4%	104% ‖ 4%
Scenario 2 (50 PRGs)	9 Players	13% ‖ 3%	13% ‖ 3%	132% ‖ 92%	127% ‖ 89%	127% ‖ 89%
	6 Players	17% ‖ 6%	17% ‖ 6%	132% ‖ 78%	153% ‖ 84%	153% ‖ 84%
	High-volume	16% ‖ 5%	16% ‖ 5%	173% ‖ 113%	193% ‖ 123%	193% ‖ 123%
	Medium-size	14% ‖ 4%	14% ‖ 4%	97% ‖ 61%	95% ‖ 56%	95% ‖ 56%
Scenario 1		84% ‖ 6%	96% ‖ 6%	99% ‖ 6%	99% ‖ 6%	113% ‖ 6%
Scenario 2		15% ‖ 5%	15% ‖ 5%	132% ‖ 85%	140% ‖ 87%	140% ‖ 87%

vehicle is replaced by the medium-size truck and when an allocation unit is used that is based on distances. Table 7 shows that in more than 50% of all cases where customer #1 does not opt for the GHG minimal supplier, he gets allocated less emissions than in the GHG minimal network configuration when the medium-size truck is used and the allocation is done based on kilometers, ton-kilometers, or volume-kilometers.

Finally, Table 8 reports how much GHG, on average, a player receives additionally per allocation method when she/he deviates from the GHG minimal network configuration. Here, the distance-based allocation units produced the best results, with an on average plus between 99 and 113% in scenario 1 (case 1), a plus of 6% in scenario 1 (case 2), a plus between 132 and 140% in scenario 2 (case 1), and a plus of around 86% in scenario 2 (case 2). We call these allocation units the 'best' ones because they allocate ('penalize') much more if a player behaves in a non-environmentally friendly manner than the other allocation schemes. To illustrate the intuition of this analysis, consider, for instance, the allocation rules 'Ton' and 'Kilometer.' For a given PRG, we firstly determine which carrier player #1 selects in the GHG minimal network configuration (say carrier 1) and the GHG 'Ton' and 'Kilometer' assign to player #1 (say 100 and 200 kg CO_2e, respectively). Then, we make player #1 deviate from the GHG minimal configuration (i.e., select carrier 2) and we determine the new 'optimal' network configuration. If 'Ton' now assigns 130 kg CO_2e to player #1 and 'Kilometer' 300 kg CO_2e, then the relative increase in the GHG assigned are 30% and 50%, respectively; i.e., the relative penalization is greater when using 'Kilometer.' The values in Table 8 report the means of these calculations over all PRGs that belong to a certain scenario-player/-vehicle configuration. Note that we use relative and not the absolute increases in the allocated GHG since the aggregation of the figures will be problematic if absolute figures are used (e.g., PRGs with particularly high overall GHG because the locations are far from each other, will strongly affect the aggregated figures). In each scenario and case (last two rows in Table 8), the lowest additional GHG emissions are allocated by the Ton- and the Volume-based methods. This means that these allocation methods penalize the focal player the least when she/he deviates from the GHG minimal configuration, i.e., these rules incorporate, according to our observations, the least incentive to behave environmentally friendly. It should be noted that, for a p-value of 5%, the distance-based methods only perform in scenario 2 significantly better than the Ton- and Volume-based methods. In order to explain the results observed, we firstly concentrate on scenario 1 case 2, where all allocation methods result in the same percentage increase. This observation is due to the fact that in almost all PRGs studied, all other suppliers also switch the selected carrier as a response to the changed behavior of supplier #1 in order to minimize the overall GHG. As the characteristics of the shipments do not change (same origin, destination, weight, and volume), the allocated emissions increase proportionally to the increase in GHG when switching from the more to the less favorable carrier. In scenario 1, the GHG increase attributed to player #1 is considerably higher in case 1 than in case 2. This observation can be explained by the fact that, in case 1, the other players do not change their behavior (i.e., do not change the carrier) in order to minimize the GHG

as much as possible. Thus, situations may occur where supplier #1 is served alone or with only one additional supplier in the newly selected carrier network. This means that (a) the GHG increase as a consequence of the suboptimal behavior of supplier #1, (b) lots of consolidation potential in terms of a joint use of trucks is lost (many semi-filled trucks move through the transport networks), and (c) the overall GHG are distributed among a reduced number of players in the single transport networks. Concerning scenario 2, the distance-based methods show in all settings significantly higher percentage scores than 'Ton' and 'Volume.' This observation can be explained by the fact that the GHG increase attributed to player #1 in the cases of 'Ton' and 'Volume' purely originates from the additional GHG that are produced in the carrier network when player #1 changes the selected supplier. Since the weight and the volume of the single shipments do not change, the allocated emissions increase proportionally to the increase in GHG when player #1 switches from a more to a less favorable supplier. When distance-based allocation methods are used, the additional GHG attributed to player #1 are considerably higher since not only the overall GHG of the transport network increase when player #1 changes the supplier but the allocation keys change as well. To be precise: when using the allocation units 'Ton' and 'Volume' the allocation keys do not change since the characteristics of the shipments, in terms of weight and volume, remain the same. In contrast, when customer #1 places her/his order at another supplier, the allocation keys change since the distance between customer #1 and the selected supplier change. Thus, when customer #1 selects a supplier that does not minimize the overall GHG, she/he will be penalized (a) through the overall increase in GHG as a consequence of her/his suboptimal selection and (b) through a change in the allocation key, which will be particularly unfavorable for her/him when the shipment's points of origin and destination are far away from each other. When comparing the cases 1 and 2, the percentage increase is lower in case 2 since the other customers can also switch the supplier in order to minimize the overall GHG. Thus, the effect on the overall GHG is not so high when customer #1 changes her/his behavior. Also note that, in case 2, where the other customers are also allowed to change the supplier, the allocation keys will change even more.

4.3 Conclusions from the numerical study

The purpose of this research is to contribute to the identification of the most meaningful apportionment principle for the allocation of GHG emissions to shipments in road freight transportation among all possibilities named in EN-16258. In this context, the most meaningful allocation unit is the one that bridges best four criteria: pragmatism, accuracy, fairness, and the GHG minimizing incentive. As has been shown in previous research projects, all EN-16258 allocation units are pragmatic. Thus, we aim to contribute to a more harmonized declaration of the transport GHG in supply chains by presenting an analytical framework for studying the performance of different allocation schemes with respect to accuracy, fairness, and the GHG minimizing incentive.

As for accuracy, and considering scenario 1 only, our results largely confirm the findings reported by Kellner (2016) and Kellner and Schneiderbauer (2019), who also observed that the allocation unit 'Kilometer' is the most accurate one. Kellner and Schneiderbauer (2019) explain the good performance of 'Kilometer' with respect to accuracy with the great impact that distance traveled has from a physical point of view on the GHG from transportation. Our research shows that 'Kilometer' is also the most accurate allocation unit when the transport scenarios of the prior research projects are extended. Whereas the travelling salesman settings studied by Kellner (2016) only take the physical effect of a shipment on GHG into account, the vehicle routing models presented by Kellner and Schneiderbauer (2019) allow additionally to consider the effect of the single shipment on GHG via its effect on the routing of the shipments. This research extends the scope of analysis of the prior research as it considers three aspects: (1) the physical effect of a shipment on GHG via mass and distance, (2) the effect of the single shipment on the routing of the vehicles and thus on GHG, and (3) the fact that a shipment can be transported by different carriers. In scenario 2, interestingly, we observe that the Kilometer-based rule performs worse than the other rules. This is particularly due to fact that, in this scenario, the origin locations are not specified in advance. Thus, the distance is less relevant for the overall GHG because the origin location can be changed in order to minimize the overall GHG.

Concerning fairness, our results show that there is not one allocation method that fulfils every fairness criterion best. 'Kilometer' scores best regarding IR. Concerning CS, Core performance, Semicore performance, and Causation, the performances of the EN-16258 allocation rules do not differ significantly. Among the different allocation rules, preference may be given to the Kilometer-based allocation method as it is particularly good at Individual Rationality and does not perform worse than the other rules at CS, the Core, and the Semicore. In particular, we agree with the statement of Kellner and Schneiderbauer (2019) that a good performance at IR is more important than at CS, the Core, and at the Semicore as it is much easier for a player to verify if he gets allocated more GHG than he would receive when not cooperating than investigating all theoretical coalitions that might be formed.

The EN-16258 allocation rules also show different strengths concerning the GHG minimizing incentive. In scenario 2, the allocation rules that do not incorporate distances achieved better results than the distance-based methods. As for the increase in GHG emissions when deviating from the GHG minimal network configuration, the allocation units processing distances showed the greatest on average increase, thus penalizing a non-environmentally friendly behavior most.

Overall, we find that, depending on the aspect studied, the results may differ significantly for the two scenarios and the given conditions (i.e., number of players, vehicles used), suggesting a case-by-case recommendation. Whereas, the observations for scenario 1 largely confirm the results reported by Kellner (2016) and Kellner and Schneiderbauer (2019), concluding that 'Kilometer' performs in summary better than the other allocation schemes, the outcomes of scenario 2 do not support the findings of the prior research. Considering the results of this study and the prior research projects, we conclude that a general recommendation concerning the single best allocation rule is not possible at this stage, because the results depend on the

scenario. However, the results of this study and the prior research also suggest that there are two groups of scenarios—or, that a 'scenario' should be defined differently. To be precise, when assuming that the points of origin and destination of a shipment cannot change, then the allocation unit 'Kilometer' shows in many transport settings (travelling salesman setting, vehicle routing setting, network flow setting), and under different conditions (differing number of players, different vehicles, etc.), a good performance. On the other hand, when the origin and/or destination of a shipment can change, then the comparative strengths of the single allocation principles can change significantly. Based on these findings, we conclude that the performance of the different allocation methods depends on the definition of the term 'shipment' (in particular: are the locations fixed or not) and that more research is still required, especially when the locations can change, to understand the performance of the different allocation principles in different transport scenarios more in depth.

Concerning the generalizability of the findings with regard to a higher/realistic number of shipments, we argue that, when departing from the point of view that a transport service is a request to move a certain object with a certain mass and a certain volume from one location to another (i.e., the points of origin and destination are determined in advance; cf., scenario 1), then our findings confirm the observations of the previous research: to be specific, in the studies of Kellner (2016) and Kellner and Schneiderbauer (2019), differing numbers of shipments (up to 16) have been transported within different transport network types. In each network and for any number of players, the Kilometer-based allocation rule showed either the best performance or, when this rule was outperformed by another rule, then this result was statistically not significant. Obviously, this is not a mathematical proof that the results are valid for any numbers of players, however a strong indication of a particularly good performance of this allocation scheme. Concerning scenario 2, the results do not confirm the findings of scenario 1 and those of the prior studies. However, we argue that the setting of scenario 2 is a different one because a transport service is not seen any more as a request to move a certain object from a specific location to another as the source (the supplier) can change. In order to make more informed statements about the generalizability of the findings in those cases, more research is needed. We argue that the methodology, the setup of the experiments, and the results presented in this research may serve as a starting point for future research projects.

5 Conclusion and further research

This study extended the scope of analysis of prior research projects that analyzed the performance of the EN-16258 allocation rules to identify the most meaningful rule. While the previous studies investigated the accuracy and the fairness of the EN-16258 allocation rules in distinct road freight transport scenarios, this research introduced a novel aspect to the pollution routing game, namely the incentive power of the different allocation rules to opt for the GHG minimal way of running a road freight transport network. For this purpose, we presented two novel transport scenarios that do not only allow studying the aspects that the prior research projects

already analyzed, but also the GHG minimizing incentive of diverse GHG allocation rules. The results of the numerical experiments in combination with the findings from the prior studies indicate that the direct distance between the points of origin and destination of the single shipments is in many situations (not in all!) a meaningful allocation unit. On the other hand, the results of scenario 2 suggest a case-by-case recommendation and show that more research is still required to better understand the performance of the different allocation schemes in different transport settings. This is especially true since, besides the scenarios studied in this research, many other scenarios can be thought of, amongst others, by combining them. For instance, in practice, the two studied scenarios are not necessarily mutually exclusive, as it is realistic that several suppliers offer the same product from which customers need to select one (situation 2), and each supplier is responsible for selecting an LSP to execute the deliveries (situation 1). Therefore, it is necessary to carry out more sensitivity analyses, e.g., with regard to the number of players, in order to find out if the results observed in this research may be generalized and extrapolated to other transport scenarios. Notwithstanding, and regardless of the results of the numerical study, this research has contributed to a more harmonized declaration of the transport GHG in supply chains by presenting an analytical framework for studying the performance of different allocation schemes with respect to accuracy, fairness, and the GHG minimizing incentive they create.

From a methodological point of view, this research presented (a) a novel aspect for the pollution routing game, (b) two new PRG scenarios and the corresponding mathematical models, (c) a CGT based framework for studying the performance of different allocation schemes with respect to accuracy, fairness, and the GHG minimizing incentive, (d) the setup of a series of numerical experiments, and (e) a proposal for analyzing and interpreting the observations made. In this regard, we directly respond to the call for future research expressed by Kellner and Schneiderbauer (2019) and contribute to close the corresponding gap in research. Future research might further extend the analysis of the PRG, including the development of new transport scenarios that reflect a specific transport context or the use of other CGT concepts to study the apportionment problem more in depth.

From a practical point of view, the results of the numerical study contribute to a better understanding of the comparative strengths of different allocation schemes in different transport scenarios. However, more research is required to verify the generalizability of the findings presented in this research, especially in cases where the origin/destination locations are not determined in advance, as in the case of scenario 2. In particular, future research should investigate more in detail the sensitivities of the allocation methods' performance with respect to different transport variables, such as the number and the geographical positions of the origin and destination locations, the characteristics of the vehicles used, shipment sizes in terms of weights and volumes, and the size of the delivery region. The methodology, the setup of the experiments, and the results presented in this research may serve as a starting point for future research projects.

As EN-16258 contains, besides the apportionment problem, other shortcomings (Auvinen et al. 2014; Davydenko et al. 2014), we encourage researchers to give

advice on how to overcome these problems. A starting point might be the discussion of the vehicle operating system, which is an important aspect of EN-16258 because all GHG are calculated on the basis of the VOS. Another aspect might be the consideration of other modes of transport, such as maritime, air, or railway transport. Solving these problems will contribute to a more accurate, fair, and harmonized assessment of the GHG performance of different logistics networks, to the identification of best practices and to an overall reduction of GHG stemming from supply chain activities.

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