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ORIGINAL PAPER

# Assessing the environmental benefits of horizontal cooperation using a location-inventory model

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**Abstract**
As customers are aware of the climate change, eco-friendly strategies have become a competitive advantage for companies. In particular, they are aiming to reduce their carbon footprint along their supply chain. In this context, substantial $CO_2$ emissions reductions can be reached by horizontal cooperation, i.e. the collaboration of companies that work at the same level of the supply chain. In this paper, we evaluate these reductions using a location-inventory model which minimizes facility opening, transportation, cycle inventory, ordering and safety stock costs. To understand the impact of different market and partners characteristics on the $CO_2$ emissions reductions, we compute a large set of numerical experiments, varying several key parameters (vehicles capacity, facility opening cost, inventory holding cost, order cost, demand variability and distances). Results show that horizontal cooperation reduces $CO_2$ emissions by 16% on average. Moreover, horizontal cooperation is more effective in decreasing the carbon footprint of companies with low facility opening costs and low order costs, carrying expensive products (high unit holding cost) on a market with a high demand variability and a vast market area.

**Keywords** $CO_2$ emissions reductions · Environmental benefits · Horizontal cooperation · Supply chain network design · Location-inventory problem

## 1 Introduction

Nowadays, the climate disruption caused by the increase in greenhouse gases is beyond doubt (Ramanathan and Feng 2009; Nair 2016). The objective is to keep the global

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temperature to a maximum of 2 °C above pre-industrial level (UNFCCC 2015). This increase represents the limit to avoid dangerous impacts on humanity. Experts evaluate that the possibility to limit the global warming to 1.5 °C is already out of reach and that two thirds of the available resources for keeping the warming below 2 °C has already been consumed (Rogelj et al. 2016). Citizens and politicians are now aware of the climate change and look to limit its expansion (Harris et al. 2011b). Therefore, public authorities develop restrictive regulations notably aiming at limiting the pollution produced by companies (Linton et al. 2007). For their part, customers increase the pressure on companies by purchasing preferentially responsible products (Comas Martí et al. 2015). Eco-friendly strategies become a competitive advantage for companies (Seuring and Müller 2008). For example, Walmart aims to reduce $CO_2$ emissions at each step of its supply chain and displays the estimated carbon footprint of their products (Plambeck 2007; Dekker et al. 2012). Results show an increase of the brand loyalty, a greater attractiveness for new customers, a higher employee motivation and a better relationship with public authorities (Pagell and Wu 2009).

Companies wishing to reduce their carbon footprint should most likely look at their transportation emissions. The road transportation represents about 15% of the current gas emissions in the European Union and around 25% in Asia and in the Pacific (Pérez-Bernabeu et al. 2015). The potential reduction related to transportation is high as about 27% of the national transport in European countries are empty hauls and as vehicles are loaded on average at 57% of their weight capacity (Creemers et al. 2017). Related to this subject, the literature has seen a growing interest for green supply chain management (Linton et al. 2007; Seuring and Müller 2008). Green supply chain management is defined as “the integration of environmental thinking into supply chain management, including product design, supplier selection and material sourcing, manufacturing processes, product packaging, delivery of the product to the customers, and end-of-life management of the product after its uses” (Sundarakani et al. 2010, p. 43). However, environmental objectives are often in opposition with the current trend aiming at a lower stock level and a higher delivery frequency to propose a better service to customers. Indeed, this leads to centralize the distribution centers, increasing the distances, and underusing vehicles in order to respect short delivery times (Harris et al. 2011b).

In this context, cooperation represents a rare opportunity to reduce the costs, to improve the service level and to reduce the environmental impact at the same time (Seuring and Müller 2008; Seuring 2013). Two types of cooperation exist. Firstly, vertical cooperation consists in a partnership with the upstream and the downstream actors of the supply chain (Christopher 2016). Second, horizontal cooperation, which is the focus of this paper, is the cooperation between firms that operate at the same level of the supply chain (Cruijssen 2006). Horizontal cooperation brings several benefits as it allows companies to share resources (vehicles, buildings, knowledge). Customers are delivered by closer warehouses, reducing the distances and thus positively impacting the transportation costs. Vehicles carry products from different companies, improving the loading rates and reducing the total number of trips per period needed. Furthermore, the total number of vehicles delivering a retailer over a given period is reduced, but a specific product is delivered more often, improving the service to customers. The reduction of the traveled distances and the more efficient loading of vehicles impact positively the ecological footprint of cooperating companies, reducing the $CO_2$ emissions generated (Ballot and Fontane 2010).

In this paper, our goal is to assess the environmental benefits of horizontal cooperation as well as how the partners and market characteristics influence them. We propose a location-inventory model and compare the $CO_2$ emissions of companies when they use independent or joint supply networks. The model minimizes the total logistics cost, and then the $CO_2$ emissions reductions are computed, a posteriori. It simulates a company firstly aiming to reduce its supply chain costs and then analyzing the environmental benefits as a consequence. Contrary to most studies in the horizontal cooperation literature where the models only account for the transportation costs, we also consider the other main logistics costs such as the facility opening, the ordering, the cycle inventory and the safety stock costs. The transportation costs are proportional to the number of trips required and not to the quantity of products carried. This particularity allows us to account for the improvement in the vehicle loading rate, and to better assess the possible cost and $CO_2$ emissions reductions related to transportation. In order to understand the variations in $CO_2$ emissions reductions, we run a large number of experiments (26,220) with various market and partners characteristics (the vehicles capacity, the facility opening cost, the inventory holding cost, the ordering cost, the demand variability, the number of partners). Our goal is to present valuable managerial insights to help companies assessing the potential environmental benefits they can get when cooperating, as a function of their characteristics.

The remainder of the paper is structured as follows. In the next section, we review the related literature and position the contribution of our paper. In Sect. 3, we present our problem setting and our location-inventory model. In Sect. 4, we discuss our experimental results and managerial insights. Finally, we end the paper in Sect. 5 with a conclusion summarizing our main results and proposing ideas for future research.

## 2 Literature review

Supply chain management constantly looks for the best tradeoff between costs, $CO_2$ emissions, quality and service level (Paksoy et al. 2013). Supply chains are often optimized in isolation, while cooperation with other companies offers new improvement perspectives. In this paper, our goal is to assess and analyze the environmental benefits of horizontal cooperation, using a location-inventory model. In this literature review, we thus discuss these three fields in supply chain management: inventory-location models, horizontal cooperation and sustainability. We briefly present them individually in the following and then focus on the literature at their crossroads.

Supply chain network design and inventory-location problems have raised more and more attention in the last decades [see the reviews by Melo et al. (2009) and Farahani et al. (2015)]. Since facility location has a notable impact on inventory and shipment costs, integrated inventory-location models represent a step forward (Kaviani 2009). Inventory-location models, integrating both strategic (such as DCs locations) and tactical (such as inventory decisions) strategies, lead to better solutions than using two models consecutively (Zhang and Unnikrishnan 2016). They have been proposed for many different configurations, including for example closed-loop supply chains

**Table 1** Overview of the literature exploring at least two of the three fields (horizontal cooperation, sustainability, and location models) as seen in the three first columns. The other columns show the inclusion of inventory decisions, demand uncertainty, and a $CO_2$ emissions computation accounting for the vehicle load

| | Coop. | Sust. | Locat. | Inv. | Uncert. | $CO_2$ Load. |
|---|---|---|---|---|---|---|
| Ballot and Fontane (2010) | √ | √ | – | – | – | √ |
| Juan et al. (2014) | √ | √ | – | – | – | √ |
| Pérez-Bernabeu et al. (2015) | √ | √ | – | – | – | √ |
| Danloup et al. (2015) | √ | √ | – | – | – | √ |
| Soysal et al. (2018) | √ | √ | – | √ | √ | √ |
| Harris et al. (2009) | – | √ | √ | – | – | – |
| Harris et al. (2011a) | – | √ | √ | – | – | – |
| Diabat et al. (2013) | – | √ | √ | – | – | √ |
| Comas Martí et al. (2015) | – | √ | √ | √ | √ | √ |
| Verdonck et al. (2016) | √ | – | √ | – | – | – |
| Hacardiaux and Tancrez (2018) | √ | – | √ | √ | √ | – |
| Ouhader and El Kyal (2017) | √ | √ | √ | – | – | √ |
| This paper | √ | √ | √ | √ | √ | √ |

(Özceylan and Paksoy 2013; Özceylan et al. 2014). Atamtürk et al. (2012) demonstrate that location-inventory problems can be modeled by conic quadratic mixed-integer programs and efficiently solved on commercial optimization softwares.

The carbon footprint of a company and its supply chain are clearly intertwined. Green supply chain management aims to find the right trade-off between operational and environmental performance measures (Paksoy et al. 2011). Studies in this field indicate that substantial $CO_2$ emissions reductions can be achieved by only slightly increasing the logistics costs (Fahimnia et al. 2015), depending on the product characteristics (Comas Martí et al. 2015). It has also been shown that the vehicle speed may have a strong impact on the $CO_2$ emissions, larger than noise, driver wages or fuel costs for example (Paksoy and Özceylan 2014). Nonetheless, the supply chain has to be taken as a whole to avoid that a reduction in a stage moves the pollution in another part of the chain (Chaabane et al. 2012).

Finally, supply chain management has to account for the interactions with other companies. Companies can interact in a competitive way (Rezapour et al. 2011; Farahani et al. 2014) or, in the opposite, they can look for synergies among their supply chains and cooperate. Comparing the coalition gains found by various studies, we observe that benefits highly vary with the market and partners characteristics. The cost reduction ranges from around 5 to 30% (Ergun et al. 2007; Cruijssen et al. 2007; Cuervo et al. 2016). Some real-world cases of horizontal cooperation show promising results. Hageback and Segerstedt (2004) study the case of twenty companies carrying their goods in common vehicles in a rural area, leading to a coalition gain around 30%. Frisk et al. (2010) analyzed the horizontal cooperation of eight forest companies and showed savings ranging from 5 to 15%.

Our work is closer to papers which are at the crossroads of two of these three fields or, even more, of the three of them. Table 1 presents on these papers, and allows to position our paper in the literature. Only few papers analyze the environmental benefits of horizontal cooperation (Sundarakani et al. 2010). Ballot and Fontane (2010) study the environmental impact of merging the distribution centers of two French retail chains. The reduction in transportation emissions was estimated to be around 25%. Juan et al. (2014) solve a cooperative vehicle routing problem through the use of backhaul strategies, which reduces the distance-based costs by 16% and the environmental footprint by about 24%. Pérez-Bernabeu et al. (2015) solve a capacitated vehicle routing problem in which shippers share the fleet of vehicles to reduce the traveled distances and the environmental impact. Results show a high variation in the $CO_2$ emissions reductions, ranging from 50 to 92% depending on the geographical distribution of the customers. Danloup et al. (2015) analyze a collaborative distribution, sharing vehicles between retailers, in a simulation study of a food supply network. The cooperation leads to a reduction of $CO_2$ emissions by at least 26%. Finally, Soysal et al. (2018) analyze the energy use of transportation operations in an inventory routing problem with multiple suppliers. Their results show again a high sensitivity to the parameters. The emission reductions due to cooperation vary between 8 and 33%. These references show the high dependence of $CO_2$ emissions reductions to the market and partners characteristics, and the challenge to distinguish their respective impact.

The literature studying sustainability in supply chains using location models gained in importance in recent years (Chen et al. 2014). Harris et al. (2009) develop an uncapacitated facility location model to minimize the costs, the environmental impact and the uncovered demand. They observe that the optimal number of depots is lower if we consider an economic than an environmental goal. Harris et al. (2011a) propose a multi-objective facility location model, minimizing the costs and the environmental impact of operations, and conclude that a low cost solution produces the highest $CO_2$ emissions. Diabat et al. (2013) propose a model minimizing the facility opening, transportation, and carbon emissions costs for forward and reverse supply chains. Their analysis shows that $CO_2$ emissions reductions are directly affected by supplier selection and by carbon emissions costs. Finally, Comas Martí et al. (2015) propose an inventory-location model taking demand uncertainty into account. They show that the characteristics of a product and the presence of specific carbon policies strongly affect the supply chain network design.

To the best of our knowledge, only two papers study horizontal cooperation using a facility location model, while most papers on cooperation focus on vehicle routing problems. Verdonck et al. (2016) analyze the benefits of cooperation in the context of a supply network and include the location decisions of joint facilities (DCs). The sharing of DCs reduces the total cost by 9.1%, due to the shared facility opening costs as well as the shortened distances. Hacardiaux and Tancrez (2018) also evaluate the cost savings due to horizontal cooperation, including more logistics costs (facility opening, transportation, cycle inventory, ordering and safety stock costs) and the possibility to carry the products of different companies in the same vehicle. On a large set of numerical experiments, they get an average coalition gain of 22.4%. Neither of these two papers look at the environmental benefits of horizontal cooperation.

Finally, besides the current paper, only one paper is at the intersection of the three fields, looking to assess the environmental benefits of horizontal cooperation using a location model, as seen in Table 1. Ouhader and El Kyal (2017) propose a multicriteria optimization model combining facility location and routing decisions, which maximizes the cost reduction and considers the $CO_2$ emissions as a constraint (using an $\epsilon$-constraint method). Inventory decisions and demand uncertainty are not considered. They analyze their results on a case with 3 suppliers and 40 customers, and show that cooperation can reduce $CO_2$ emissions, but that there is a clear trade-off between transportation costs and $CO_2$ emissions. In this paper, to assess the environmental benefits of horizontal cooperation, we use an inventory-location model, which includes location and allocation decisions, demand uncertainty, lead time, and inventory decisions regarding the cycle inventory as well as the safety stocks at DCs and at retailers. Our model allows to efficiently get a unique solution, and thus to perform a large number of experiments and reach reliable results. Several valuable insights occur from the analysis of these results, regarding the impact of market and partners characteristics. In sum, compared to Ouhader and El Kyal (2017), our paper differs mainly in the fact that we account for more logistics costs and decisions, and in the fact that we derive insights from a large number of experiments.

The main contribution of our paper is to assess and analyze the $CO_2$ emissions reductions that companies may expect when cooperating in a joint supply network. We analyze in details the impact of several market and partners characteristics (vehicles capacity, facility opening cost, inventory holding cost, order cost, demand variability, distances, and number of partners) and compare the reductions in costs and $CO_2$ emissions. For this, we use a location-inventory model that integrates the main logistics costs and parameters, and can be solved efficiently. We then run a large number of experiments (26,220) in order to reveal the impact of these market and partners characteristics and reach reliable managerial insights for companies interested in the environmental benefits of cooperation.

## 3 Location-inventory model

In this section, we present the problem setting, the mathematical model and the $CO_2$ emissions computation. Our goal is to assess the environmental benefits obtained when companies collaborate through a joint supply network, sharing vehicles and facilities. For this, we compare the $CO_2$ emissions when companies operate independently, in the stand-alone case, and when they decide to collaborate, in the cooperation case. Our problem setting is illustrated in Fig. 1. We consider two or more companies, each offering a single product. The companies' products are distinct and non substitute, and have their own cycle inventory and safety stock. We consider an infinite time horizon. The retailer demand for a specific product is normally distributed. Safety stocks allow to satisfy the uncertain demand during the lead time (which is proportional to the traveled distance), with a probability determined by the service level.

Comparing the two delivery networks in Fig. 1, we see that, in the stand-alone case, each company owns a central plant and (optimally located) distribution centers (DCs). A company delivers its products directly to the retailers, from a single DC (single sourcing). In the cooperation case, the companies use a joint supply network, except for the plants which keep producing the distinct products independently. The

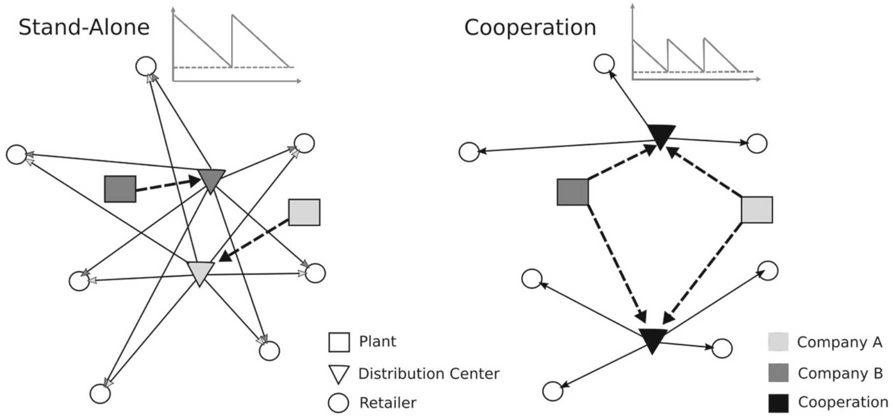


**Fig. 1** Comparison of the delivery networks, and inventories at a retailer, for the stand-alone and cooperation cases

products are stored in new joint DCs, but each product has its own inventory. They are then carried together in joint vehicles directly to the common retailers, from a single DC. The distances between DCs and retailers are reduced as companies share DCs, reducing the transportation costs and the safety stocks. Moreover, the higher delivery frequency when cooperating allows to reduce the cycle inventories.

The companies decide to use a joint supply network knowing the diverse benefits of cooperation: cost reduction, carbon footprint reduction and customer service improvement. However, we suppose that the companies' main objective from cooperating is to reduce their logistics costs. The $CO_2$ emissions reductions is an additional motivation to cooperate, which they want to assess. Therefore, when designing the supply network, the focus is given on cost reduction. To simulate this context, the objective of our optimization model is cost minimization, while the resulting ecological footprint reduction is assessed afterwards. Note that both costs and carbon footprint reductions are firstly coming from the improved transportation efficiency, and are thus generally going in the same direction (see Sect. 4).

The objective function of our model is thus to minimize the total logistics cost which is composed of the facility opening, the transportation, the ordering, the cycle inventory and the safety stock costs. The model determines the number and the location of the distribution centers, the allocation of the flows, as well as inventory decisions regarding the shipment size and the safety stocks. Importantly, the shipment size being a decision of the model allows us to account for the improvement of the vehicle loading rate due to cooperation, which is essential to the costs and carbon footprint reductions. In the following, we present first the notations and then our location-inventory model, which has the form of a conic quadratic mixed integer program.[1]

*Indexes*

$d = \{1, \ldots, n_d\}$ for distribution center (DC) potential locations;

[1] The model is detailed in Hacardiaux and Tancrez (2018), and can be seen as an extension of the models proposed by Atamtürk et al. (2012) and by Schuster Puga and Tancrez (2017).

$r = \{1, \ldots, n_r\}$ for retailers;
$i = \{1, \ldots, n_i\}$ for the companies and their products.

*Parameters*

$F_d$: Fixed cost for opening DC $d$, in €/period;
$T$: Transportation cost per km for a vehicle, in €/km;
$D_{dr}$: Distance between DC $d$ and retailer $r$, in km;
$H_r^i$: Unit inventory holding cost at retailer $r$ for product $i$, in €/(item·period);
$h_d^i$: Unit inventory holding cost at DC $d$ for product $i$, in €/(item·period);
$C_{dr}$: Vehicle capacity from DC $d$ to retailer $r$, in items/vehicle;
$K_d^i$: Fixed cost for placing an order to the plant producing product $i$ at DC $d$, in €/order;
$z_\alpha^i$: Standard normal deviation associated with service level $\alpha^i$ at retailers, for product $i$;
$LT_{dr}$: Lead time between DC $d$ and retailer $r$, in periods;
$LT_d^i$: Lead time between the central plant producing product $i$ and DC $d$, in periods;
$\lambda_r^i$: Mean demand for product $i$ at retailer $r$, in items/period;
$\Lambda_r$: Mean demand for all products at retailer $r$, in items/period, i.e. $\Lambda_r = \sum_i \lambda_r^i$;
$\sigma_r^i$: Standard deviation of the demand for product $i$ at retailer $r$, in items/period;
$\epsilon^{ev}$: $CO_2$ emissions emitted by an empty vehicle in kg/km;
$\epsilon^{fv}$: $CO_2$ emissions emitted by a fully loaded vehicle in kg/km.

*Decisions variables*

$y_d = 1$ if DC $d$ is opened, 0 otherwise;
$y_{dr} = 1$ if DC $d$ serves retailer $r$ (for all products), 0 otherwise;
$Q_{dr}$: Total shipment size (for all products) from DC $d$ to retailer $r$, in items/vehicle;

$$\begin{aligned} min \quad & \sum_d F_d\, y_d + \sum_{d,r} T\, D_{dr} \frac{\Lambda_r}{Q_{dr}}\, y_{dr} + \sum_{d,r,i} H_r^i \frac{Q_{dr}}{2} \frac{\lambda_r^i}{\Lambda_r}\, y_{dr} \\ & + \sum_{d,i} \sqrt{2\, K_d^i\, h_d^i}\, v_{1d}^i + \sum_{d,r,i} H_r^i\, z_\alpha^i\, \sigma_r^i \sqrt{LT_{dr}}\, y_{dr} + \sum_{d,i} h_d^i\, z_\alpha^i \sqrt{LT_d^i}\, v_{2d}^i \end{aligned}$$

s.t.

$$\sum_r \lambda_r^i\, (y_{dr})^2 \leq (v_{1d}^i)^2 \qquad \forall d, i \tag{1}$$

$$\sum_r (\sigma_r^i)^2\, (y_{dr})^2 \leq (v_{2d}^i)^2 \qquad \forall d, i \tag{2}$$

$$\sum_d y_{dr} = 1 \qquad \forall r \tag{3}$$

$$y_{dr} \leq y_d \qquad \forall d, r \tag{4}$$

$$v_{1d}^i, v_{2d}^i \geq 0 \qquad \forall d, i \tag{5}$$

$$y_{dr}, y_d \in \{0, 1\} \qquad \forall d, r \tag{6}$$

The terms of the objective function represent, respectively, the costs of facility opening, transportation (cost per vehicle), cycle inventory at retailers, cycle inventory and ordering at DCs (supposing an EOQ structure), safety stocks at DCs and safety stock at retailers (for satisfying the uncertain demand during the lead time). The shipment size, $Q_{dr}$, can be inferred from the second and third term. It is given by the following formula: $Q_{dr} = min\left(C_{dr}, \sqrt{\frac{2\,T\,D_{dr}\,\Lambda_r}{\sum_i H_r^i\,\lambda_r^i/\Lambda_r}}\right)$. As $Q_{dr}$ is only proportional to parameters, it can be computed a priori, and is not treated as a variable when solving our model [see Tancrez et al. (2012) for the single product case]. Constraints (1) and (2) define the auxiliary variables $v_{1d}^i$ and $v_{2d}^i$ which allow to move the non-linearities from the objective function (cycle inventory, order costs and safety stock costs at DCs) to the constraints. The objective is then linear and the constraints are either linear or conic quadratic (using $y_{dr} = y_{dr}^2$ and $y_d = y_d^2$). This leads to a conic quadratic mixed-integer program, which can be solved using commercial solvers [see Atamtürk et al. (2012) or Schuster Puga and Tancrez (2017) for more details]. Constraints (3) insure that each retailer is assigned to exactly one DC. Constraints (4) insure that a retailer can be served by a DC only if the latter is opened. Constraints (5) impose non-negativity for the auxiliary variables, while constraints (6) enforce the binary nature of decision variables $y_{dr}$ and $y_d$.

After solving our location-inventory model, we get the cost-minimizing supply chain for cooperating companies, and the resulting $CO_2$ emissions coming from transportation can be computed. In particular, our model includes the shipment size decisions, and the loading rate of the vehicles can thus be used to reach a more accurate $CO_2$ emissions estimation (compared to one supposing full truckloads). The improvement of the loading rate due to cooperation is accounted for in the computation of the $CO_2$ emissions. We apply the $CO_2$ emissions computation proposed by Pan et al. (2013), which is commonly accepted in the literature (Moutaoukil et al. 2013, 2015; Danloup et al. 2015; Ouhader and El Kyal 2017). The $CO_2$ emissions per km due to the supply of a retailer $r$ from the DC $d$ are made up of two parts: the $CO_2$ emissions emitted by an empty vehicle per km ($\epsilon^{ev}$), multiplied by the number of trips ($\Lambda_r/Q_{dr}$), and the $CO_2$ emissions per km due to the vehicle load ($\epsilon^{fv} - \epsilon^{ev}$), multiplied by the volume of products expressed in full vehicles ($\Lambda_r/C_{dr}$). To get the total $CO_2$ emissions of the supply chain, these emissions per km are multiplied by the distance, $D_{dr}$, and summed for all selected shipments (where $y_{dr} = 1$), leading to the following formula.

$$\sum_{d,r} \left[\epsilon^{ev}\frac{\Lambda_r}{Q_{dr}} + (\epsilon^{fv} - \epsilon^{ev})\frac{\Lambda_r}{C_{dr}}\right] D_{dr}\; y_{dr} \tag{7}$$

This equation illustrates clearly the importance of the loading rate (shipment size decisions, $Q_{dr}$) and of the traveled distance ($D_{dr}$, related to the location decision) on the $CO_2$ emissions. In particular, when the loading rate improves ($Q_{dr}$ increases), the $CO_2$ emissions will decrease. In summary, the two ways to reduce the $CO_2$ emissions are to reduce the traveled distances, opening more DCs, and to improve the loading rate, which leads to a lower number of trips per period.

## 4 Computational experiments

In this section, we apply our optimization model and the $CO_2$ emissions computation on a large set of experiments in order to assess the environmental benefits of horizontal cooperation. We first present our experimental setting and then discuss our experimental results, analyzing the impact of each individual parameter on the $CO_2$ emissions reductions and looking at the relation between the $CO_2$ emissions and the logistics costs reductions.

### 4.1 Experimental setting

In our experiments, we first look at two companies that are similar in terms of size and market characteristics (we will look at more companies farther in this section). The parameter values reflecting these characteristics are detailed in Table 2. Sixty retailers are randomly located in a square with a width of 500 or 1000 km (*Width*). The retailers locations are also the possible locations for the distribution centers. This assumption is common and well accepted in the facility location literature (see e.g. Nozick and Turnquist 2001; Shen et al. 2003; Atamtürk et al. 2012). The expected demand for each product and each retailer is randomly generated within the interval [50, 250], which allows to have retailers of different sizes. The vehicles capacity is an important parameter in our experiments, as improving the loading rate of vehicles is an important objective of horizontal cooperation. For that reason, we use ten percentages (*Cap%*) that give the portion of retailers which are not constrained by the vehicle capacity in the stand-alone case (e.g. when $Cap\% = 10$, the capacity is highly restrictive: 10% of the shipments are made with their optimal quantities in the stand-alone case and the other 90% are limited by the capacity). Lead times between DCs and retailers are directly proportional to the distance, assuming an average speed of 50 km/h. The order lead time from all DCs to all plants is fixed equal to the average lead time from all potential DCs to all retailers. The $CO_2$ emissions emitted by a vehicle are set to 0.857 kg/km for an empty vehicle ($\epsilon^{ev}$) and 1.209 kg/km for a full vehicle ($\epsilon^{fv}$). These values are obtained applying the formula proposed by Hickman et al. (1999), considering a heavy-duty vehicle (maximum load of 25 tons) driving at a speed of 50 km/h, and ignoring the gradient of the road (as Pan et al. 2013). The other parameter values [demand variability ($CV$), service level ($\alpha$), transportation cost ($T$), facility opening cost ($F_d$), order cost ($K_d^i$), holding costs at DCs ($h_d^i$) and at retailers ($H_r^i$)] are detailed in Table 2.

This parameter setting leads to create 1620 combinations ($2 \cdot 3 \cdot 10 \cdot 3 \cdot 3 \cdot 3$). Five different maps with different retailer locations and demands are randomly generated, resulting in 8,100 settings in our basic set of experiments. We run the model when companies stand-alone (2 cases) and when they cooperate. A total of 24,300 experiments is thus run for this analysis (additional experiments with more than two partners are discussed in Sect. 4.2). This large number of experiments allows us to deeply study the impact of various company and market characteristics, and eventually derive reliable managerial insights on the value of horizontal cooperation for improving the environmental footprint of a company. The model is implemented in CPLEX

**Table 2** Parameters values for the numerical experiments

| Parameter setting | |
|---|---|
| $Width$ | (500, 1000*) km |
| $CV$ | (0.4*, 0.7, 1*) |
| $Cap\%$ | (10*, 20, 30, 40*, 50, 60, 70*, 80, 90, 100*) |
| $F_d$ | (1000*, 2000*, 4000*) €/week |
| $K_d^i$ | (250*, 500, 1000*) €/order |
| $h_d^i = H_r^i$ | (0.25*, 0.50, 1*) €/item·week |
| $T$ | 1€/km |
| $\alpha$ | 97.5% |
| $z_\alpha^i$ | 1.96 |
| $\epsilon^{ev}$ | 0.857 kg/km |
| $\epsilon^{fv}$ | 1.209 kg/km |

and run on a 3.2 GHz computer with 8 GB of RAM. We limit the computational time per instance to 30 min, and get an average optimality gap of 0.14% for the stand-alone cases and 0.35% for the cooperation cases.

### 4.2 $CO_2$ emissions reductions analysis

In this section, we analyze the results of our experiments, and what they reveal on the environmental benefits of horizontal cooperation. We look at the relative savings in $CO_2$ emissions, in percentages, as they are independent from the size of the company and allow a good comparison between different configurations. In Table 3, we present the average $CO_2$ emissions reductions obtained depending on four parameters: area size (*Width*), facility opening cost ($F_d$), order cost ($K_d^i$) and unit holding cost ($H$).

Overall, we observe an average $CO_2$ emissions reduction of 16.3%, showing the significant environmental benefits that horizontal cooperation can bring. However, we also see that the $CO_2$ emissions reductions vary significantly depending on the parameter combination, ranging from 6.6 to 29.9%. The range is even larger when we differentiate the capacity percentages, leading to an emissions reduction range between 0.2 and 35.9%. This large variation in $CO_2$ emissions reductions is consistent with the literature (Pérez-Bernabeu et al. 2015; Soysal et al. 2018). It highlights the need to better understand the impact of each parameter, to determine when it is more environmentally beneficial for a company to collaborate and why. In comparison, the analysis of the cost reduction shows a narrower variation, ranging from around 14.6 to 30.5% with an average of 22.4% (Hacardiaux and Tancrez 2018).

The reductions in $CO_2$ emissions come from two main factors. Firstly, companies share their distribution centers, and the cost for opening them. This leads companies to open more DCs when they cooperate, compared to when a company is independent. In Table 3, we see that cooperating companies open 1.95 DCs on average, compared to 1.51 DC for an independent company. As a consequence, DCs are better spread

**Table 3** Average $CO_2$ emissions reductions due to horizontal cooperation when the area size (*Width*), the facility opening cost ($F_d$), the order cost ($K_d^i$) and the unit holding cost ($H = h_d^i = H_r^i$) are varied Below each reduction, we present the average number of DCs for one company in the stand-alone and cooperation cases and then the loading rate of vehicles in both cases. Each value corresponds to an average over 150 experiments (10 capacity percentages, 3 coefficients of variation and 5 maps)

| $K_d^i$ | $H$ | *Width* = 500 | | | *Width* = 1000 | | | Average (all cases) |
|---|---|---|---|---|---|---|---|---|
| | | $F_d = 1000$ | $F_d = 2000$ | $F_d = 4000$ | $F_d = 1000$ | $F_d = 2000$ | $F_d = 4000$ | |
| 250 | 0.25 | 25.6% | 11.8% | 6.8% | 26.9% | 24.0% | 7.2% | 17.0% |
| | | 1.27\|2.05 | 1.00\|1.18 | 1.00\|1.00 | 2.42\|3.45 | 1.06\|1.78 | 1.00\|1.02 | 1.29\|1.75 |
| | | 0.81\|0.88 | 0.82\|0.92 | 0.82\|0.93 | 0.75\|0.85 | 0.81\|0.89 | 0.81\|0.93 | 0.80\|0.90 |
| | 0.5 | 20.9% | 19.7% | 7.8% | 17.2% | 29.9% | 14.3% | 18.3% |
| | | 2.13\|2.85 | 1.06\|1.55 | 1.00\|1.03 | 3.45\|4.17 | 1.54\|2.63 | 1.00\|1.29 | 1.70\|2.25 |
| | | 0.79\|0.90 | 0.82\|0.92 | 0.82\|0.93 | 0.77\|0.89 | 0.78\|0.85 | 0.81\|0.92 | 0.80\|0.90 |
| | 1 | 21.0% | 26.5% | 13.0% | 16.0% | 26.2% | 25.2% | 21.3% |
| | | 2.69\|3.49 | 1.31\|2.16 | 1.00\|1.23 | 4.01\|4.81 | 2.56\|3.55 | 1.08\|1.85 | 2.11\|2.85 |
| | | 0.78\|0.89 | 0.81\|0.88 | 0.82\|0.93 | 0.80\|0.91 | 0.76\|0.86 | 0.81\|0.88 | 0.80\|0.89 |
| 500 | 0.25 | 20.2% | 9.5% | 6.8% | 26.6% | 19.9% | 6.8% | 15.0% |
| | | 1.14\|1.66 | 1.00\|1.10 | 1.00\|1.00 | 1.92\|2.87 | 1.02\|1.56 | 1.00\|1.01 | 1.18\|1.53 |
| | | 0.81\|0.91 | 0.82\|0.93 | 0.82\|0.93 | 0.76\|0.85 | 0.81\|0.90 | 0.81\|0.93 | 0.80\|0.91 |
| | 0.5 | 20.7% | 14.9% | 7.4% | 18.8% | 25.1% | 11.2% | 16.4% |
| | | 1.57\|2.14 | 1.02\|1.32 | 1.00\|1.02 | 3.03\|3.71 | 1.34\|2.15 | 1.00\|1.17 | 1.49\|1.92 |
| | | 0.78\|0.88 | 0.82\|0.92 | 0.82\|0.93 | 0.76\|0.88 | 0.79\|0.87 | 0.81\|0.93 | 0.80\|0.90 |
| | 1 | 17.8% | 21.9% | 10.5% | 13.9% | 26.5% | 21.3% | 18.6% |
| | | 2.26\|2.82 | 1.17\|1.77 | 1.00\|1.13 | 3.73\|4.23 | 2.09\|3.05 | 1.04\|1.63 | 1.88\|2.44 |
| | | 0.79\|0.90 | 0.82\|0.91 | 0.82\|0.93 | 0.79\|0.90 | 0.76\|0.86 | 0.82\|0.90 | 0.80\|0.90 |

**Table 3** continued

| $K_d^i$ | $H$ | $Width = 500$ | | | $Width = 1000$ | | | Average (all cases) |
|---|---|---|---|---|---|---|---|---|
| | | $F_d = 1000$ | $F_d = 2000$ | $F_d = 4000$ | $F_d = 1000$ | $F_d = 2000$ | $F_d = 4000$ | |
| | | 13.6% | 7.9% | 6.8% | 21.0% | 14.2% | 6.6% | 11.7% |
| | 0.25 | 1.06\|1.31 | 1.00\|1.04 | 1.00\|1.00 | 1.58\|2.20 | 1.01\|1.31 | 1.00\|1.00 | 1.11\|1.31 |
| | | 0.82\|0.92 | 0.82\|0.93 | 0.82\|0.93 | 0.77\|0.88 | 0.81\|0.92 | 0.81\|0.93 | 0.81\|0.92 |
| | | 15.1% | 10.8% | 6.8% | 19.4% | 20.6% | 9.5% | 13.7% |
| 1000 | 0.5 | 1.21\|1.52 | 1.00\|1.15 | 1.00\|1.00 | 2.30\|2.93 | 1.14\|1.69 | 1.00\|1.10 | 1.27\|1.57 |
| | | 0.81\|0.92 | 0.82\|0.93 | 0.82\|0.93 | 0.75\|0.87 | 0.80\|0.89 | 0.81\|0.93 | 0.80\|0.91 |
| | | 15.8% | 14.1% | 8.2% | 13.8% | 21.9% | 15.9% | 14.9% |
| | 1 | 1.63\|1.98 | 1.07\|1.34 | 1.00\|1.05 | 3.19\|3.53 | 1.69\|2.38 | 1.01\|1.36 | 1.60\|1.94 |
| | | 0.79\|0.90 | 0.82\|0.92 | 0.82\|0.93 | 0.76\|0.88 | 0.78\|0.88 | 0.82\|0.92 | 0.80\|0.91 |
| Average (all cases) | | 19.0% | 15.2% | 8.2% | 19.3% | 23.1% | 13.1% | **16.3%** |
| | | 1.66\|2.20 | 1.07\|1.40 | 1.00\|1.05 | 2.85\|3.55 | 1.49\|2.23 | 1.01\|1.27 | 1.51\|1.95 |
| | | 0.80\|0.90 | 0.82\|0.92 | 0.82\|0.93 | 0.77\|0.88 | 0.79\|0.88 | 0.82\|0.92 | 0.80\|0.90 |

and closer to retailers. In our results, the average (accounting for delivery frequencies) distance traveled between a DC and a retailer[2] is reduced by 7.1% when cooperating. Secondly, when companies cooperate, they benefit from sharing vehicles and improve the vehicle loading rate. In Table 3, we see that the vehicle loading rate is improved from 80 to 90%, leading to a reduction in the total number of trips per period of 12.5% on average. In the following, these two main factors are used to explain the impact of various market and partners characteristics on the $CO_2$ emissions reductions. With this goal, Tables 4 and 5 show the impact of various characteristics on the $CO_2$ emissions reductions and on these two main factors: the number of DCs and average distance on one side, the loading rate and delivery frequency on the other side.

#### 4.2.1 Market and partners characteristics

The $CO_2$ emissions reductions that companies can achieve when cooperating depend strongly on the characteristics of their supply chains, their market and the partnership. In this section, we discuss the influence of seven parameters reflecting these characteristics: the facility opening cost, the area size, the order cost, the inventory holding cost, the vehicle capacity, the demand variability and the number of partners.

*Facility opening cost.* As seen in Tables 3 and 4, the $CO_2$ emissions reductions due to cooperation tend to be larger with inexpensive facilities but it evolves non-monotonically with the facility opening cost (19.1%, 19.2% and 10.7% with $F_d$ = 1000, 2000 and 4000 respectively, as seen in Table 4). When the facility opening costs are low ($F_d = 1000$), companies open many inexpensive DCs, especially if they cooperate as they then share the facility costs. We observe in Table 4 that cooperation leads to increase the number of DCs by 31.2%, and to reduce the average traveled distance by 9.4%. Furthermore, cooperation also helps maintaining a higher loading rate (+ 15.2%), which reduces the number of trips per period by 13.3%. In the end, the shorter distances and better loading rate lead to significant $CO_2$ emissions reductions of 19.1%. Then, with medium facility opening costs ($F_d = 2000$), the DCs become expensive for the stand-alone companies, which decrease their number, while cooperating companies still open a large number of them, as they share the costs. As seen in Table 4, the difference in number of DCs is at its highest, with 40.2%. The average traveled distance is thus even more reduced with cooperation (− 10.6%) than previously. On the other side, the savings in terms of number of trips (− 12.1%) decrease as stand-alone companies improve their loading rate to offset the longer distances. The two effects tend to even out, leading to quite stable $CO_2$ emissions reductions (− 19.2%) when facility opening costs are low or medium. Finally, with large facility opening costs ($F_d = 4000$), DCs become too expensive even for cooperating companies. A large part of the benefits related to the traveled distances reduction when companies cooperate is lost (from − 10.6 to − 1.3%, see Table 4). In Table 3, we observe that, with $F_d = 4000$, the stand-alone companies use a unique DC and cooperating companies open only slightly more than one DC. On a side note, Table 3 also

[2] The average distance traveled between a DC and retailer is computed as follows: $\sum_{d,r} \frac{\Lambda_r}{Q_{dr}} D_{dr}\, y_{dr} / \sum_{d,r} \frac{\Lambda_r}{Q_{dr}} y_{dr}$.

**Table 4** Average impact (in %) of horizontal cooperation on the vehicle loading rate, number of trips per period ($Nb.Trips$), number of DCs per company ($Nb.DCs$), average distance traveled between a DC and a retailer ($Avg.Dist.$) and $CO_2$ emissions reductions ($CO_2$ $Reduc.$) depending on the value of various parameters

| Param. | $F_d$ | | | $Width$ | | $K_d^i$ | | $h_d^i = H_r^i$ | | $Cap\%$ | | $CV$ | | $Avg.$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1000 | 2000 | 4000 | 500 | 1000 | 250 | 1000 | 0.25 | 1 | 10 | 100 | 0.4 | 1 | *All* |
| $Loading\ Rate$ | + 15.2 | + 13.5 | + 14.6 | + 14.4 | + 14.4 | + 13.9 | + 15.1 | + 14.4 | + 14.1 | + 2.5 | + 35.7 | + 14.5 | + 14.4 | + 14.4 |
| $Nb.Trips$ | − 13.3 | − 12.1 | − 12.1 | − 12.5 | − 12.6 | − 12.3 | − 12.8 | − 12.5 | − 12.5 | − 3.5 | − 26.2 | − 12.4 | − 12.6 | − 12.5 |
| $Nb.DCs$ | + 31.2 | + 40.2 | + 14.6 | + 23.3 | + 34.0 | + 36.6 | + 19.6 | + 25.2 | + 33.3 | + 50.8 | + 7.1 | + 28.0 | + 29.4 | + 28.6 |
| $Avg.Dist.$ | − 9.4 | − 10.6 | − 1.3 | − 4.5 | − 9.7 | − 10.0 | − 3.8 | − 5.4 | − 9.0 | − 15.7 | − 1.6 | − 6.8 | − 7.5 | − 7.1 |
| $CO_2$ $Reduc.$ | − 19.1 | − 19.2 | − 10.7 | − 14.1 | − 18.5 | − 18.9 | − 13.4 | − 14.6 | − 18.3 | − 17.9 | − 21.8 | − 16.0 | − 16.7 | − 16.3 |

**Table 5** Impact (in %) on the vehicle loading rate, number of trips per period, number of DCs per company, average distance traveled between a DC and a retailer ($Avg.\ Dist.\ DC - Ret.$) and $CO_2$ emissions in the stand-alone (*Alone*) and in the cooperation cases ($Coop.$), due to the increase of each parameter individually from its lowest to its highest values in our setting

| Parameter | Change | Loading rate | | Number of trips | | Number of DCs | | Avg. Dist. DC-Ret. | | $CO_2$ emissions | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Alone | Coop. | Alone | Coop. | Alone | Coop. | Alone | Coop. | Alone | Coop. |
| $F_d$ | 1000 → 4000 | + 4.4 | + 3.9 | − 15.0 | − 13.6 | − 55.3 | − 59.6 | + 46.7 | + 59.0 | + 29.3 | + 39.1 |
| $Width$ | 500 → 1000 | − 2.5 | − 2.5 | − 21.2 | − 21.3 | + 43.5 | + 51.4 | + 73.9 | + 64.5 | + 30.5 | + 23.5 |
| $K_d^i$ | 250 → 1000 | + 0.6 | + 1.5 | − 4.7 | − 5.0 | − 21.9 | − 29.7 | + 9.4 | + 17.0 | + 6.1 | + 13.3 |
| $h_d^i = H_r^i$ | 0.25 → 1 | − 0.7 | − 1.1 | + 114.0 | + 113.7 | + 56.1 | + 57.5 | − 16.3 | − 20.1 | + 79.0 | + 69.9 |
| $Cap\%$ | 10 → 100 | − 43.4 | − 25.0 | − 40.0 | − 54.1 | − 34.5 | − 50.3 | + 6.0 | + 25.7 | − 42.8 | − 44.8 |
| $CV$ | 0.4 → 1 | − 0.3 | − 0.4 | + 1.1 | + 0.9 | + 4.6 | + 5.0 | − 1.7 | − 2.5 | − 1.0 | − 1.9 |

shows that the threshold at which DCs become too expensive even for cooperating companies is higher for a larger market area (as $CO_2$ emissions reductions are already decreasing at $F_d = 2000$ with $Width = 500$, but not with $Width = 1000$). Naturally, companies are willing to invest more in DCs when they need to cover large market areas. Furthermore, with large facility costs ($F_d = 4000$), as the number of DCs decreases and distances increase, stand-alone companies are under pressure to load their vehicles efficiently, and the benefits of cooperation related to the improvement of the loading rate are thus also reduced. These combined effects lead to a drastic decrease in the $CO_2$ emissions reductions (− 10.7%). In Table 5, we observe that the $CO_2$ emissions increases faster in the cooperative case (+ 39.1%) than in the stand-alone case (+ 29.3%), when $F_d$ goes from 1000 to 4000. In sum, when the facility opening cost increases, stand-alone companies are affected earlier as cooperating companies share the additional costs, leading to stable $CO_2$ emissions reductions at first. When DCs become too expensive even for cooperating companies, a large part of the savings in traveled distance is lost and $CO_2$ emissions reductions drop.

*Area size*. When retailers are located on a larger area (*Width*), we observe in Tables 3 and 4 that the $CO_2$ emissions reductions tend to increase (from 14.1 to 18.5% when *Width* doubles). Looking at Table 5, we observe that on larger maps, the number of DCs increases by 43.5% in the stand-alone case and by 51.4% when companies collaborate as they share the facility costs. The average distance increases less (+ 64.5%) when companies cooperate than in the stand-alone case (+ 73.9%). The positive impact of cooperation on traveled distances is thus even more significant on a larger area (− 9.7% vs. − 4.5% in Table 4). As seen in Tables 4 and 5, the benefits of cooperation related to the loading rate and the number of trips are only barely affected by the *Width*. In sum, the environmental benefits from horizontal cooperation are higher for partners delivering retailers in a large market, as cooperation allows to better cover the area with more DCs.

*Order cost*. As seen in Table 3, an increase of the order cost leads to smaller $CO_2$ emissions reductions when cooperating. We observe in Table 5 that the increase in $CO_2$ emissions due to a higher order cost is larger in the cooperation case (+ 13.3%) than in the stand-alone case (+ 6.1%), reducing the average $CO_2$ emission reduction from 18.9 to 13.4% (see Table 4). This is due to the fact that a high order cost is more detrimental to companies with many DCs since they have to order from each of them to the central plant. The cooperating companies are thus more affected by an increase in $K_d^i$. Moreover, to limit the impact of increasing order costs, the number of DCs is reduced, losing part of the environmental benefits related to the shorter distances. We see in Table 4 that, when the order cost changes from $K_d^i = 250$ to $K_d^i = 1000$, the benefits in traveled distance decrease from 10 to 3.8%. However, this drastic decrease is mitigated by the ability of cooperating companies to better load the vehicles (+ 15.1%) to limit the number of trips made on these longer distances. To conclude, companies with a low order cost will get even more environmental benefits from collaborating, as opening many DCs will not hurt them through order costs.

*Inventory holding cost*. Looking at Table 3, we observe that a higher unit holding cost leads to higher $CO_2$ emissions reductions from cooperation. In Table 5, we see

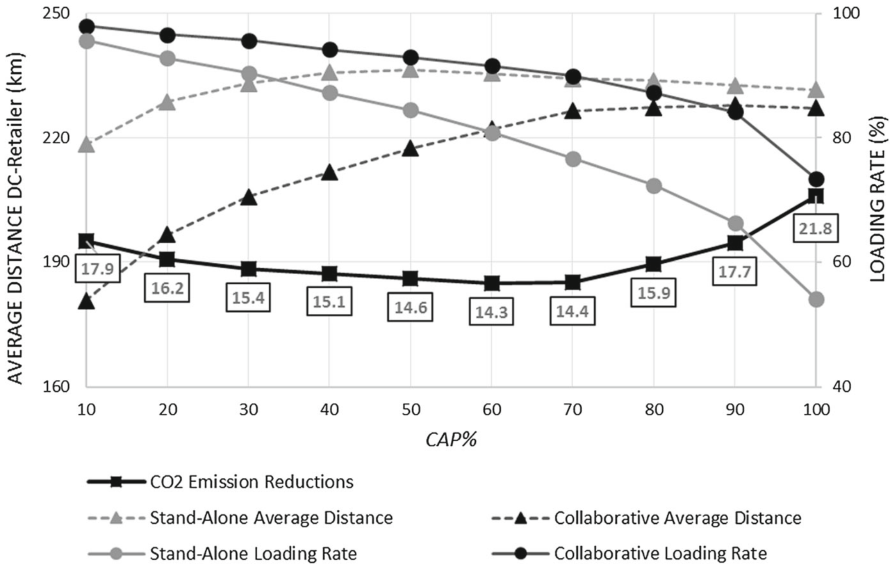


**Fig. 2** Evolution of the $CO_2$ emissions reductions, the average loading rate and the average distance between a DC and a retailer, when companies stand-alone and when they collaborate, as a function of the vehicles capacity

that cooperation allows to mitigate the increase in $CO_2$ emissions due to a higher holding cost (+ 69.9% vs. + 79%). In order to limit the inventory costs in both cases, the number of trips increases considerably and more DCs are opened to get closer to retailers (see Table 5). As cooperating companies share facility costs, they open a higher number of joint DCs to limit more significantly the increase in distances traveled, and thus also the $CO_2$ emissions (from $H = 0.25$ to $H = 1$, the average distance between the DCs and the retailers decreases by 16.3% in the stand-alone case and 20.1% in the cooperation case, see Table 5). In Table 4, it appears clearly that the benefits from cooperation related to the distances reduction are stronger with a high inventory holding cost (− 9% vs. − 5.4%). In summary, horizontal cooperation is more environmentally beneficial when the cost of inventory is high as joint DCs allow to mitigate the increase in the number of trips.

*Vehicle capacity*. Looking at Table 4, we see that the $CO_2$ emissions reductions tend to increase (from 17.9 to 21.8%) when the vehicle capacity goes from very small to very large (or, equivalently, going from a very bulky product to a very small one). However, their evolution in between these extreme values reveals to be non-monotonic. This is related to the radically opposite impact of the vehicle capacity on the two main factors leading to $CO_2$ emissions reductions, which can be seen in Table 4. When the capacity increases, the benefits in traveled distances drop from − 15.7 to − 1.6% while the improvement of the loading rate rises from + 2.5 to + 35.7%. Figure 2 illustrates the non-monotonic evolution of the $CO_2$ emissions reductions, as they first decrease and then increase. When the capacity is low, we see in Fig. 2 and Table 4 that the benefits in terms of loading rate are very low, as stand-alone companies are able to load the small vehicle efficiently. Their optimal shipment size is often larger than the vehicle capacity. On the opposite, the benefits in terms of distance reduction is at its highest. Due to the limited vehicle capacity, the delivery frequency is high and distances must be shortened as much as possible. Cooperating companies thus have a distinct advantage in this regard as they are able to open more DCs, which they share the costs of. When the vehicle capacity increases, we see in Fig. 2 that the $CO_2$ emissions reductions decrease and the two factors have opposite evolutions. At first, the necessity to limit distances dwindles quickly, and so does the advantage of cooperation in this regard, while stand-alone companies are still able to load their vehicles efficiently. The $CO_2$ emissions reductions are thus lower with a medium vehicle capacity as stand-alone companies own a decent number of DCs and well loaded vehicles. When the vehicle capacity becomes larger (from around $Cap\% = 70\%$), cooperating companies benefit more from this large capacity, as they have larger quantities to transport than stand-alone companies (which have already mostly reached their optimal shipment size). As seen in Fig. 2, the average loading rate decreases less quickly for cooperating companies, and the difference increases compared to stand-alone companies. This clearly outweights the reduced advantage in terms of distance reduction, and the $CO_2$ emissions reductions increases noticeably. For the largest capacity, the $CO_2$ emissions reductions from cooperation reach 21.8%, thanks to a considerable reduction in the number of trips (− 26.2%, and + 35.7% in the loading rate, see Table 4), while the distances are barely reduced (− 1.6%). In brief, the $CO_2$ emissions reductions from cooperation are larger when the vehicle capacity is unsuited for stand-alone companies, i.e. either too small (leading to a high delivery frequency, and the need for many DCs) or too large (leading to an inefficient loading rate). Overall, a large capacity leads to the highest $CO_2$ emissions reductions.

*Demand variability*. As seen in Tables 3 and 4, a more uncertain demand leads to larger $CO_2$ emissions reductions (from 16 to 16.7% when $CV$ increases from 0.4 to 1). The safety stock level is proportional to the lead time and thus to the distance. A higher demand uncertainty thus leads to an increase in the number of DCs, to reduce distances. As cooperating companies share the facility opening costs, they open more DCs (see Table 5). The average distance with the retailers is thus reduced more when cooperating (− 2.5%) than in the stand-alone case (− 1.7%). Moreover, we observe in Table 4 that a more uncertain demand does not significantly impact the savings related to a better loading rate. In brief, horizontal cooperation is more beneficial in terms of $CO_2$ emissions when demand variability is high, as it helps reducing lead times.

*Number of partners*. To question the influence of the number of partners in the cooperation, we conduct additional experiments. A subset of the parameter values tested in the main set of experiments is used (see the asterisks in Table 2) resulting in 96 parameter combinations ($4 \cdot 2 \cdot 3 \cdot 2 \cdot 2$). As we still use five different maps and as we test configurations with 3 and 4 partners, it leads to a total of 1920 experiments. The main results are displayed in Table 6. First, we observe that a broader partnership leads to larger $CO_2$ emissions reductions: up to 33.8% with 4 partners. In the stand-alone case, as expected, the $CO_2$ emissions and the number of DCs are proportional to the number of partners, while the loading rate stays stable. In contrast, when more companies cooperate, they benefit from economies of scale by better loading the vehicles (up to 95% loading rate), and being able to use more DCs for which they share the opening

**Table 6** Average $CO_2$ emissions reductions of cooperations with 2, 3 and 4 partners ($CO_2$ *Reduc.*) The other columns give the average $CO_2$ emissions ($CO_2$), loading rate ($LR$) and total number of distribution centers ($DCs$) in the stand-alone and in the cooperative cases. The difference between values is presented between them

| | $CO_2$ *Reduc.* | Stand-alone | | | Cooperation | | |
|---|---|---|---|---|---|---|---|
| | | $CO_2$ | $DCs$ | $LR$ | $CO_2$ | $DCs$ | $LR$ |
| 2 Partners | 19.3% | 18,044 | 3.7 | 77% | 14,555 | 2.4 | 88% |
| | + 9.4% | + 51.2% | + 1.9 | +1% | + 33.6% | + 0.5 | + 5% |
| 3 Partners | 28.7% | 27,278 | 5.6 | 78% | 19,444 | 2.9 | 93% |
| | + 5.1% | + 29.1% | + 1.9 | +0% | + 23.3% | + 0.3 | + 2% |
| 4 Partners | 33.8% | 36,231 | 7.5 | 78% | 23,975 | 3.2 | 95% |

costs (up to 3.2 DCs compared to 1.9 per stand-alone company). The transportation is thus more and more efficient, on shortened distances, leading to clear $CO_2$ emissions reductions. However, the potential economies of scale are less and less potent when the number of partners increases, and the marginal $CO_2$ emissions reductions thus decrease. For example, the loading rate becomes more and more difficult to improve with each newcomer, as it get close to 100%. Similarly, we see in Table 6 that cooperating companies open less new DCs with each newcomer. Indeed, the opening of new DCs is less and less profitable as there are already well distributed, and the distances are thus no longer sufficiently reduced. In summary, a larger partnership has a positive impact on the $CO_2$ emissions but the marginal benefit decreases with each newcomer.

### 4.2.2 $CO_2$ emissions reductions and logistics costs

Now that we analyzed the impacts of the different partners and market characteristics on the $CO_2$ emissions, it is interesting to compare them with the impacts of these characteristics on the logistics costs (detailed in Hacardiaux and Tancrez 2018). On average, for our parameter setting (see Table 2), the logistics costs are reduced by 22.4% when companies collaborate. This cost reduction comes, in order of importance, from the reduced inventory at retailers (11.4%), the more efficient transportation (6.9%) and the opening of joint facilities (6%). On the opposite, the inventory and order costs at DCs (− 1.9%) tend to increase when companies collaborate.

Interestingly, we observe in Table 7 that all parameters do not impact the benefits of cooperation in the same way for $CO_2$ emissions and for logistics costs. The change has the same direction for four parameters: the vehicle capacity, the order cost, the area size and the number of partners. When vehicles are larger or products smaller (*Cap%*), collaboration is particularly valuable to help fill the vehicles more efficiently, which is positive for both costs and $CO_2$ emissions. When the order costs ($K_d$) increase, it incentivises companies to ship larger batches, leading to better loaded trucks, and thus reducing the benefits of collaboration. When the market area gets larger (*Width*), collaboration is particularly beneficial in terms of costs and carbon footprint as more DCs can be opened to cover the area, and as the longer distances are covered with more efficient transportation. When the number of partners increases (#*Part.*), it reduces

**Table 7** Impact (in %) on the average $CO_2$ emissions reductions ($Emiss.\ Reduc.$) and on the average logistics costs reductions ($Cost\ Reduc.$) due to horizontal cooperation, of the increase of each parameter individually from its lowest to its highest values in our setting

| Parameter change | $F_d$ | $Width$ | $K_d$ | $h_d^i = H_r^i$ | $Cap\%$ | $CV$ | $\#Part.$ |
|---|---|---|---|---|---|---|---|
| | 1000 → 4000 | 500 → 1000 | 250 → 1000 | 0.25 → 1 | 10 → 100 | 0.4 → 1 | 2 → 4 |
| $Emiss.\ Reduc.$ | − 8.5% | + 4.4% | − 5.5% | + 3.7% | + 3.9% | + 0.7% | + 14.5% |
| $Cost\ Reduc.$ | + 3.5% | + 0.5% | − 3.1% | − 3.1% | + 7.1% | − 1.2% | + 13.4% |

both the costs and the carbon footprint as more synergies are possible among more cooperating companies. We can thus already conclude that partnerships with more partners, with low order costs, using vehicles with a large capacity and delivering their products to a vast market have to be particularly encouraged, as they are even more beneficial in terms of costs and carbon footprint.

For the three other parameters, the facility opening cost, the unit holding cost and the demand variability, we see in Table 7 that the changes go in opposite directions. This can be understood from the origins of the economical and environmental benefits. The environmental benefits only come from transportation while the economical benefits depend on the trade-off between the various logistics costs. It can be noted that the three parameters are related to the non-transportation costs, i.e. the facility opening and inventory costs. When the unit facility opening cost increases ($F_d$), cooperation helps mitigating the increase in the total cost as facility opening costs are shared, and as companies can ultimately decide to share a unique DC. On the opposite, the environmental benefits fade as cooperating companies are not able to better distribute their DCs due to their excessive cost. When the holding cost increases ($h_d^i = H_r^i$), the transportation frequency will tend to rise to keep inventory levels low, thus pushing loading rates downwards. Cooperation helps keeping transportation efficient (high loading rate), and is thus particularly beneficial for $CO_2$ emissions when holding cost are high. However, when looking at the total cost, including inventory costs, this improvement in transportation efficiency is slower than the increase of the total cost, leading to cooperation being less beneficial (proportionally) in terms of cost when inventory is expensive. When demand variability increases ($CV$), the lead times tend to be reduced to limit the safety stocks at retailers (which outweigh those at DCs). When cooperating, as the DCs opening costs are shared, even more DCs will be opened to help reducing lead times. The distances will thus be more reduced, leading to a larger reduction of $CO_2$ emissions. However, as for the previous parameter, the increase of the total cost, including inventory costs, prevails, leading to cooperation being less beneficial in terms of cost with more variable demand. In conclusion, companies with high facility opening costs, carrying cheap products (low unit holding cost) on a market with low demand variability are particularly incentivised to collaborate for cost saving, but their $CO_2$ emissions will tend to be less reduced. On the opposite, companies with cheap facilities delivering expensive products on a market with large demand variability will profit less in terms of logistics costs reductions but can expect particularly good $CO_2$ emissions reductions.

## 5 Conclusion

Recently, companies turn towards horizontal cooperation in order to improve cost-effectiveness as well as customer service, but the environmental impact of cooperation is often overlooked. This paper analyzes the environmental benefits for companies to use a joint supply chain network, and investigates the features that influence those benefits to understand when horizontal cooperation is particularly fruitful. For this, we apply a location-inventory model integrating the main logistics costs such as facility opening, transportation, cycle inventory, ordering and safety stock costs. The companies' main objective is the reduction of the total cost, and the assessment of the possible $CO_2$ emissions reductions is computed a posteriori. The transportation cost is accounted per vehicle and shipment size decisions are included so that an important benefit of collaboration, the improvement of the vehicle loading rate, is accurately assessed. We perform a total of 26,220 experiments varying the parameters values (i.e. vehicle capacity, facility opening cost, inventory holding cost, ordering cost, demand variability and number of partners) and the network setting.

From these experiments, we infer valuable managerial insights to help companies assessing the potential environmental benefits they can get when cooperating, depending on their characteristics. The $CO_2$ emissions reductions range from around 0 to 36% with an average around 16%. Horizontal cooperation allows more $CO_2$ emissions reductions for companies with low facility opening costs, a large vehicle capacity (or small size products) and low order costs, carrying expensive products (high unit holding cost) on a vast market with a high demand uncertainty. Moreover, a higher number of partners leads to higher $CO_2$ emissions reductions, even if the marginal environmental benefit is smaller with each new entrant. Finally, varying the market and partners characteristics, we observe that the logistics costs and the $CO_2$ emissions evolve generally in the same direction, excepted for the facility opening cost, the unit holding cost and the demand variability which have opposite effects.

This research could be extended in several directions to circumvent some limitations and explore other approaches. Firstly, additional partners or market characteristics could be included in our model, e.g. capacity constraints to DCs and retailers, delivery time restrictions, or other uncertainty types than demand uncertainty (possibly with approaches such as robust optimization or fuzzy logic). We could also explore the potential $CO_2$ emissions reductions allowed by the reduction of the inventory, which depends on the product nature (i.e. perishability, product size, storage temperature, etc.). Moreover, other environmental indexes than $CO_2$ emissions, such as $NO_X$ or $SO_2$, could be studied. Furthermore, one could analyze the case where companies do not primarily promote costs reductions over $CO_2$ emissions reductions. For example, a multi-objective model could give more weight to the $CO_2$ emissions reductions in the managerial decisions, and attempt to find the best trade-off between costs and $CO_2$ emissions.

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