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Abstract

Anecdotal evidence shows that logistics parks are highly attractive for logistics firms. The co-location of logistics firms provides benefits such as greater availability of logistics personnel, access to other locations, and resource sharing. Despite the importance of these benefits in the location decisions of logistics firms, traditional facility location models do not consider them. This study therefore develops a model that accounts explicitly for one of the benefits, namely, the opportunity to combine transport flows. By collaboratively outsourcing transportation to a logistics service provider, co-located shippers can reduce their transport costs. However, locating in a logistics concentration area that is outside the center of gravity of customer demand results in additional shipping distances, suggesting the need to trade off the cost advantages and disadvantages that result from a location in a logistics concentration area. Shippers can use the proposed model to determine whether it is optimal to locate in a logistics concentration area. Numerical experiments show that on average, it is beneficial to locate in a logistics concentration area if it is within a distance that equals 0.15 times the square root of the surface of the region from the center of gravity of customer demand. In addition, firms obtain more gains from locating in a logistics concentration area if their shipment sizes are relatively small.

Keywords: Logistics, Location decision, Spatial concentration, Co-location.

1 Introduction

Logistics clusters are developing worldwide. Port areas in Rotterdam and Singapore, intermodal hubs in Chicago and Memphis, and logistics parks in Zaragoza and Guangzhou are highly attractive locations for logistics companies. In an extensive study of these logistics clusters, Sheffi (2012) concludes that this attractiveness can be explained by the synergies resulting from co-location of logistics companies. A location in a logistics cluster grants a logistics company good access to logistics personnel, other important global locations, and shared resources. Furthermore, companies located in logistics clusters build relationships with other firms more easily, based on their developed trust and collaboration (Sheffi, 2012), which are increasingly important in rapidly changing environments. In addition, Van den Heuvel et al. (2012a,b) empirically confirm the relevance of these synergies in two Dutch provinces: logistics companies in logistics concentration areas are more accessible, have better access to repair and maintenance facilities, enjoy improved expansion opportunities, and are more likely to combine transport and storage capacity compared to logistics companies not located in these areas.

Considering these advantages, should all logistics companies simply locate in logistics concentration areas? To address this question, we focus on a shipper that must choose a location for a new (regional) distribution center. Traditionally, this decision would reflect the location of customers that need to be supplied from that distribution center. If instead the location decision depends mainly on the desire to locate in a logistics concentration area, the firm might accrue additional transport costs, especially if the logistics concentration area is distant from the center of gravity of customer demand.

Accordingly, individual firms need to know how to determine whether they should locate in logistics concentration areas. Although the facility location problem has received substantial attention in supply chain management literature (e.g., Drezner and Hamacher, 2004; Klose and Drexl, 2005; Daskin, 2008; Melo et al., 2009; Baron et al., 2011), no existing models explicitly consider synergies through co-location, even though such synergies can be highly valuable for supply chain management (Bozart et al., 2007). Locating in a logistics concentration area offers the option of sharing transport resources with other logistics companies located in the same area, that is, of combining transport flows. Although other synergies due to the co-location of logistics firms may be hard to quantify, the opportunity to combine transport flows can be modeled explicitly, because it directly influences transportation costs.

Accordingly, unlike most facility location models that determine the optimal location on the basis of customer demand, such that they consider only the company's supply chain and transport flows, our model acknowledges that the possibility of combining transport flows with those of companies operating in other supply chains directly influences transport costs. We thus present a new way to model transportation costs in facility location models to determine the optimal location of a (new) distribution center. With a location in a logistics concentration area, a company increases the probability of combining transport flows with other logistics firms, and thus lowering costs, due to its proximity to many other logistics firms. In turn, it may be optimal to locate in a logistics concentration area, even if that area is not located in close proximity of the center of gravity of customer demand.

Our proposed model explicitly investigates the trade-off between the benefits of combining transport flows in a logistics concentration area against the costs of traveling greater distances to reach customers. With this model, a shipper confronted with a location decision can determine with what distance between the center of gravity of customer demand and the logistics concentration area it is optimal to locate in the logistics concentration area. To model the shipper's transport costs, we use a continuous approximation of the freight rates of logistics service providers. By collaborating with other shippers in the logistics concentration area, our focal shipper obtains lower freight rates, because the high network density of the transport network of the collaborating shippers decreases the transport costs for the logistics service provider. In identifying the maximal distance between the center of gravity of customer demand and the logistics concentration area, we demonstrate that the optimal location for a distribution center depends on the characteristics of the shipments that the company makes and its opportunities to combine transport flows. Note that our focus is on the reduction of transportation costs resulting from a location in a logistics concentration area, whereas a company can also decide to increase the flexibility to the customer, by decreasing shipment sizes.

We acknowledge various facility location models, which Daskin (2008) classifies as analytic, continuous, network, and discrete facility location models. Analytic facility location models typically assume that demand is uniformly distributed over a service area and facilities can be located anywhere within the area. Continuous facility location models anticipate that demand arises only at discrete locations. Network models predict demand and facility locations on the basis of a network of nodes and links. Finally, in discrete facility location models, facilities get restricted to a finite set of candidate locations. We adopt an analytic model, which uses a minimal number of parameters and therefore best enables us to identify the effects of opportunities to combine transport flows in logistics concentration areas in facility location models. Furthermore, because the other types of facility location models account for different transport volumes per customer, they define the optimal location according to the distribution of demand over the customers and the location of the logistics concentration area relative to the largest customers, which is not relevant for our study.

The remainder of this article is structured as follows: Section 2 describes the benefits of horizontal collaboration by shippers and the increased probability of finding collaboration partners in logistics concentration areas. We present the model in Section 3. Section 4 numerically specifies the influence of the different parameters on the location decision. Finally, we present model extensions in Section 5 and conclude in Section 6.

2 Horizontal collaboration and logistics concentration areas

Horizontal collaboration occurs when two or more unrelated or competing organizations cooperate to share information or resources. Horizontal collaboration in freight transport occurs when two (or more) shippers combine their shipments. By bundling their shipment requests, the shippers can negotiate better shipment rates with a common logistics service provider (LSP), on the basis of quantity discounts (Munson and Rosenblatt, 1998). Such a collaboration increases the LSP's productivity because it can perform fewer repositionings of its trucks (Ergun et al., 2007a,b; Agarwal et al., 2009) and decrease of the average distance between customers (Van Donselaar et al., 1998; Cruijssen et al., 2007a; Krajewska et al., 2008). Overlapping transportation networks based on similar source and sink regions are prerequisites for collaboration synergies (Leitner et al., 2011). Because co-located companies share at least their source or sink location, they gain opportunities to collaborate on transportation. Van den Heuvel et al. (2012a,b) show, using extensive empirical data, that logistics firms located in logistics concentration areas combine their transport flows more often than those located outside these areas. The probability that transport flows can be combined thus is higher if the facility is located in a logistics concentration area rather than elsewhere in the region.

Geographical proximity largely defines collaboration opportunities. When there is a high density of logistics firms in a logistics concentration area, many transport flows go in and out of the area, which increases the probability that transport flows can be combined. In addition, Cruijssen et al. (2007b) identify, as a critical impediment to horizontal collaboration in transport and logistics, the difficulty of finding a trusted party. Geographical proximity helps to overcome this impediment: all else being equal, the costs of exchanging information increase with greater distance between firms (Malmberg and Maskell, 1997). This effect is caused not by communication costs (Laserre, 2008) but by the need to create trust and understanding between cooperative firms, which is more likely when the firms share a common language, values, and culture. Trust and commitment in turn can promote long-term relationships (Wallenburg et al., 2011).

Although literature on collaborative transportation often assumes structural network combinations, in practice most shipments are combined only occasionally (e.g., Vanovermeire et al., 2012). That is, in practice, it remains difficult to find trustworthy partners. Companies located in logistics concentration areas can more easily build relationships based on trust and collaboration (Sheffi, 2012), because of their formal and informal (tacit) knowledge exchanges. In contrast, companies outside these areas likely struggle to build similar relationships, largely because they are external to these areas. This implies that being able to combine transport flows depends on the relationships that will be build over time with other logistics firms in the logistics concentration area. Hence, it cannot simply be checked whether there are collaboration opportunities in a logistics concentration area before a location decision is made, such that we have to model these with a certain probability. In summary, logistics concentration areas should have a positive influence on the probability on combining transport flows. The ease of building relationships in a logistics concentration area, and the difficulty doing so outside these areas, also should lead to a rapidly decreasing influence of such an area on the probability of combining transport flows with greater distance from logistics concentration areas.

3 Model

With our proposed model, we seek to determine the optimal location of a shipper's (new) distribution center, after it has outsourced transportation responsibilities to an LSP. We do not explicitly model the route planning problem, which relates primarily to tactical or operational planning levels, whereas the facility location decision is a strategic one (Eilon, 1977). Because transportation has been outsourced to an LSP, we can implicitly model the load factor of the trucks in the transportation costs. In this section, we assume that customer demand per period is smaller than or equal to a truck's capacity, so we only analyze less-than-truckload (LTL) shipments. Section 5.1 assesses the case in which customer demand is larger than one truckload (TL). In addition, whereas we assume here that there only is one logistics concentration area in the region, we relax this assumption in Section 5.2.

The model determines the long-run optimal location of a (new) distribution center by minimizing the total expected transport costs per period from this distribution center to all customers in the region. We assume that customers are uniformly distributed over the region and that the shipment size per customer per period is the same for all customers and all periods. With these assumptions, the model investigates the trade-off between a location in the logistics concentration area and the location in the center of gravity of customer demand. By locating in the logistics concentration area, transport costs are decreased due to the opportunity of combining transport flows with those of other logistics firms, but are increased due to the extra distance that has to be driven to the customers. The model compares the total transport costs related to both locations.

Define v as the shipment size in weight units per customer per period, and $\alpha = \frac{v}{W}$ as the shipment size per customer per period as a fraction of the weight of a full truckload W. We use weight units herein, but the analyses are similar with volume units. The region has size S (in squared distance units), and N_a represents the spatial density of customers (in customers per squared distance unit). The location of the distribution center is denoted by the coordinates (x, y), the location of the logistics concentration area by coordinates (x_c, y_c), and the center of gravity of customer demand by coordinates (x_g, y_g).

The remainder of this section is structured as follows: Section 3.1 describes the way of modeling the probability of combining transport flows dependent on the location of the distribution center. We present the general model that includes this probability in Section 3.2. This model does not include a specification of the per distance unit transport costs. Section 3.3 elaborates on how to model these costs, such that these can be included in the model in Section 3.4.

3.1 Probability of combining transport flows

The probability of combining transport flows with those of other logistics firms depends on the facility location. We argued in Section 2 that the probability of combining transport flows in the logistics concentration area is higher than the probability of combining transport flows at other locations. Define P_c as the probability that transport flows can be combined in the logistics concentration area, and define $P_n < P_c$ as the probability that transport flows can be combined at a location far from the logistics concentration area, that is, a location where the concentration of logistics firms does not have any influence on the probability of combining transport flows. At locations relatively close to the logistics concentration area, this influence probably is not zero, while it does decrease rapidly with greater distance from the logistics concentration area (see Section 2). The distance between the logistics concentration area and location (x, y) is defined as $d_c(x, y)$. Then, the probability that transport flows can be combined at location (x, y), denoted as $P(x, y)$, can be modeled as follows:

$$P(x, y) = P_n + (P_c - P_n) \cdot k^{-d_c(x,y)}, \tag{1}$$

where the first term in this expression is equal to the probability that transport flows can be combined at a location far away from the logistics concentration area (without any influence). The second term represents the influence of the logistics concentration area on the probability of being able to combine transport flows at location (x, y). If the facility locates in the logistics concentration area, $(x, y) = (x_c, y_c)$ and $d_c(x, y) = 0$, the probability of being able to combine transport $(P(x_c, y_c))$ flows is equal to P_c. If the facility locates far from the logistics concentration area, this probability is equal to P_n. The shape parameter $k > 0$ determines the influence of the logistics concentration area on the probability of combining transport flows, depending on the distance from the logistics concentration area, as we show in Figure 1.

3.2 General model

We define $\mathbb{E}[d(x, y)]$ as the expected distance between a random customer in the distribution region and the location of the distribution center, with coordinates (x, y). If the transport costs $c_t(\alpha)$ are defined per distance unit per period, the total transport costs per period for all customers in the region $TC(x, y)$ are defined as:

$$TC(x, y) = c_t(\alpha) \cdot \mathbb{E}[d(x, y)] \cdot S \cdot N_a. \tag{2}$$

Assuming that $c_t(\alpha)$ is independent of the facility location (x, y), the optimal location of the distribution center is in the center of gravity of customer demand. However, if transport flows can be combined, transport costs decrease, such that $c_t(\alpha)$ depends on the opportunity to combine transport flows with other logistics companies:

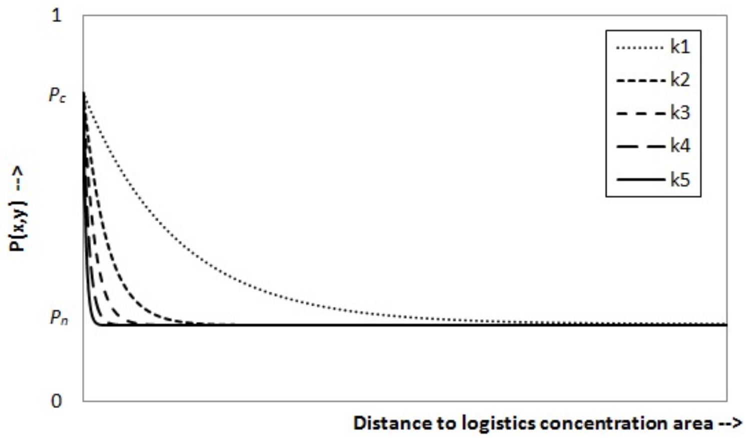


Figure 1: Influence of shape parameter k on $P(x,y)$; $k1 < k2 < k3 < k4 < k5$

$$c_t(\alpha) = \begin{cases} \overline{c_t}(\alpha) & \text{if flows cannot be combined with other logistics companies,} \\ \underline{c_t}(\alpha) & \text{if flows can be combined with other logistics companies,} \end{cases} \tag{3}$$

where $\overline{c_t}(\alpha) > \underline{c_t}(\alpha)$.

Define $\Delta c_t(\alpha) = \overline{c_t}(\alpha) - \underline{c_t}(\alpha)$ as the difference between the transport costs in case transport flows can be combined and the transport costs in case transport flows cannot be combined. Including the probability of being able to combine transport flows on a certain location, we can derive the following total transport cost function:

$$\begin{aligned} TC(x,y) &= (1 - P(x,y)) \cdot \overline{c_t}(\alpha) \cdot \mathbb{E}[d(x,y)] \cdot S \cdot N_a + P(x,y) \cdot \underline{c_t}(\alpha) \cdot \mathbb{E}[d(x,y)] \cdot S \cdot N_a \\ &= \mathbb{E}[d(x,y)] \cdot S \cdot N_a \cdot (\overline{c_t}(\alpha) - P(x,y)\Delta c_t(\alpha)). \end{aligned} \tag{4}$$

Choose the shape parameter k that determines the influence of the logistics concentration area on the probability of being able to combine transport flows at location (x, y) sufficiently high, that is, high enough to ensure that the optimal facility location is either in the center of gravity of customer demand or in the logistics concentration areas. Based on the discussion in Section 2, shippers should only gain from a location *in* the logistics concentration area, and hence, locations in between the logistics concentration area and the center of gravity of customer demand should be ruled out. The trade-off is between the logistics concentration area and the center of gravity of customer demand. Define $d_{cg} = d_c(x_g, y_g)$ as the distance between the center of gravity of customer demand and the logistics concentration area, $\mathbb{E}[d_c] = \mathbb{E}[d(x_c, y_c)]$ as the expected distance between a random customer in the region and the logistics concentration area, $\mathbb{E}[d_g] = \mathbb{E}[d(x_g, y_g)]$ as the expected distance between a random customer in the region and the center of gravity of customer demand of the region, and $\mathbb{E}[\Delta d] = (\mathbb{E}[d_c] - \mathbb{E}[d_g])/\mathbb{E}[d_g]$ as the extra expected transport distance to a random customer resulting from a location in the logistics concentration area relative to the location in the center of gravity of customer demand.

Theorem 3.1. *The logistics concentration area is the optimal location if and only if:*

$$\mathbb{E}[\Delta d] < \frac{(P_c - P_n) \cdot (1 - k^{-d_{cg}}) \cdot \Delta c_t(\alpha)}{\overline{c_t}(\alpha) - P_c \cdot \Delta c_t(\alpha)}. \tag{5}$$

Proof. From Equation 4, it follows that the total transport costs in the logistics concentration area (x_c, y_c) and in the center of gravity of customer demand (x_g, y_g), respectively, are equal to:

$$\begin{aligned} TC(x_c, y_c) &= S \cdot N_a \cdot \mathbb{E}[d_c] \cdot (\overline{c_t}(\alpha) - P(x_c, y_c) \cdot \Delta c_t(\alpha)), \text{ and} \\ TC(x_g, y_g) &= S \cdot N_a \cdot \mathbb{E}[d_g] \cdot (\overline{c_t}(\alpha) - P(x_g, y_g) \cdot \Delta c_t(\alpha)). \end{aligned} \tag{6}$$

Define $\Delta TC_{cg} = [TC(x_c, y_c) - TC(x_g, y_g)]/TC(x_g, y_g)$ as the relative total transport cost difference between these two locations. Then:

$$\Delta TC_{cg} = \frac{\mathbb{E}[\Delta d] \cdot [\overline{c_t}(\alpha) - P(x_c, y_c) \cdot \Delta c_t(\alpha)] - [P(x_c, y_c) - P(x_g, y_g)] \cdot \Delta c_t(\alpha)}{\overline{c_t}(\alpha) - P(x_g, y_g) \cdot \Delta c_t(\alpha)}. \quad (7)$$

The location decision maker is indifferent between the two options only if the total transport costs for both locations are equal, such that $\Delta TC_{cg} = 0$, which occurs if and only if

$$\mathbb{E}[\Delta d] = \frac{[P(x_c, y_c) - P(x_g, y_g)] \cdot \Delta c_t(\alpha)}{\overline{c_t}(\alpha) - P(x_c, y_c) \cdot \Delta c_t(\alpha)}. \quad (8)$$

From Equations 1 and 8, it follows that the facility will only be located in the logistics concentration area (i.e., $\Delta TC_{cg} < 0$) if and only if Equation 5 holds. □

3.3 Specification of the transport costs per distance unit

With the assumption that the shipper has outsourced its transportation to an LSP, the transport costs $c_t(\alpha)$ depend on the freight rates of the LSP. In practice, LTL rates are usually stated per weight unit for a given origin and destination. However, noting the difficulty that arises when working with actual freight rates without predetermined locations, routes, modes, or lot sizes, several researchers proposed the use of continuous functions to properly estimate actual freight rates (e.g., Swenseth and Godfrey, 1996, 2002; Tyworth and Zeng, 1998; Tyworth and Ruiz-Torres, 2000; Mendoza and Ventura, 2009). We define $f_t(v)$ as the freight rate per weight unit per distance unit, depending on the shipment weight v. Then, transport costs per distance unit can be expressed as:

$$c_t(\alpha) = v \cdot f_t(v). \quad (9)$$

Define $f_t(W)$ as the TL rate per weight unit per distance unit and $\theta = W \cdot f_t(W)$ as the transport costs of a TL per distance unit. Table 1 presents the two most often used approximations for LTL shipments, based on a power and an adjusted inverse function, and a combination of these functions. The proportional freight rate function has a worse fit with actual LTL freight rates than the power (Mendoza and Ventura, 2009) or adjusted inverse freight rate functions (Swenseth and Godfrey, 2002), so we excluded it from our analysis.

The shape parameter $0 \leq r \leq 1$ of the power freight rate function depends on specific routes. This shape parameter expresses the efficiency of the vehicle routing. For $r = 1$, the transport costs are independent of the weight of the shipment and equal to the costs of delivering a TL, and when $r = 0$, the transport costs are linear to the shipment weight. Note that we assume that if $r < 1$, the transport costs for LTL shipments are strictly less than the transport costs for a TL, which may not be true in practice. Section 5.3 relaxes this assumption.

Arcelus and Rowcroft (1991) find r values on the order of 0.62, based on actual freight rates for small orders on routes in Canada. Fitting the same function, Tyworth and Zeng (1998) find a good fit with $r = 0.33$ for representative freight rate data published by a major trucking company. The power function used by Cheung et al. (2001) indicates the best fit for a value $r = 0.5$, based on a case study of DHL in Hong Kong. Van der Vlist and Broekmeulen (2006) use an approximation of the value of r of 0.435, based on a generalization of the functions used by LSPs in the Netherlands. Mendoza and Ventura (2009) fit the power freight rate function to freight rate tables for three different routes in the United States and find values of r between 0.28 and 0.48.

Table 1: Freight rate functions and the corresponding per distance unit transport costs function

	Freight rate function	**Transport cost function**
Power	$f_t(v) = f_t(W) \cdot \left(\frac{v}{W}\right)^{-r}$	$c_t(\alpha) = \theta \cdot \alpha^{1-r}$
Adjusted inverse	$f_t(v) = f_t(W) \cdot \left[1 + \beta \cdot \frac{W-v}{v}\right]$	$c_t(\alpha) = \theta \cdot [\beta + (1-\beta) \cdot \alpha]$
Combination	$f_t(v) = f_t(W) \cdot \left[\frac{W}{v} \cdot \beta + (1-\beta) \cdot \left(\frac{v}{W}\right)^{-r}\right]$	$c_t(\alpha) = \theta \cdot [\beta + (1-\beta) \cdot \alpha^{1-r}]$

Swenseth and Godfrey (2002) indicate that a continuous approximation with rates that decrease inversely with the order size is most effective for LTL shipments, according to their prior analysis of actual freight rates on 40 alternative U.S. routes Swenseth and Godfrey (1996). This function is called the adjusted inverse function (see Table 1), where $0 \leq \beta \leq 1$ is a shape parameter determining the rate at which the freight rate increases per decrease of demand per customer. Thus β expresses the fixed drop costs per stop. For $\beta = 1$, the transport costs are independent of the weight of the shipment and equal to the costs of delivering a full truck, whereas with $\beta = 0$, the transport costs are linear to the shipment weight. From a regression analysis of a random sample of data collected for major U.S. shipping routes, Swenseth and Godfrey (2002) identify a value of β of 0.11246. Chen and Sarker (2010) use a value equal to 0.2.

As a generalization, we use a per unit transport cost function that combines the two preceding cost functions (see Table 1). If $\beta = 0$, this function reduces to the power function, and if $r = 0$, it reduces to the adjusted inverse function. We provide examples of the per distance unit transport cost function in Figure 2. Because $\theta = W \cdot f_t(W)$ is a constant determined from the freight rate table of the LSP, in Figure 2 we depict the transport costs relative to the transport costs of a TL (c_t/θ).

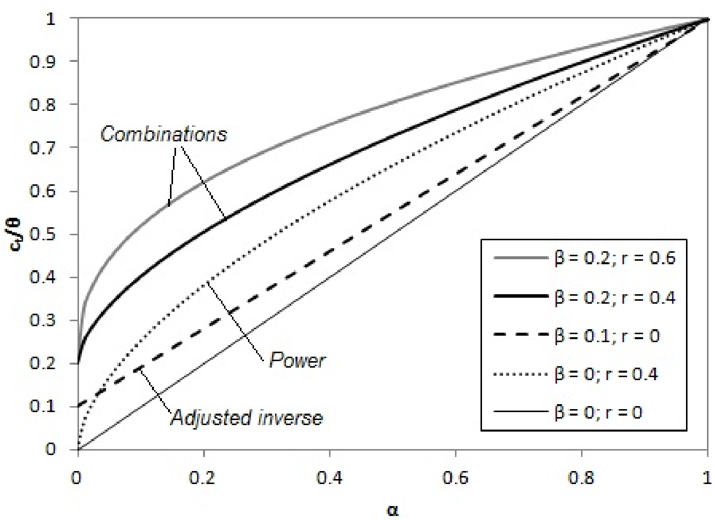


Figure 2: Transport costs per distance unit as function of the shape parameters β and r

3.4 Model with specific per unit distance transport costs function

The opportunity to combine transport flows influences the shape parameters of the per unit transportation cost function. If transport flows can be combined, freight rates decrease, such that r and/or β decrease, resulting in lower per customer transport costs. The overall effect of the combination of transport flows on the freight rates, depends on the characteristics of the flows. If the combination of flows results in a denser transportation network (i.e. demand points are closer together), the shape parameter r decreases, because this parameter depends on the efficiency of the vehicle routing. The parameter β, representing the fixed drop costs per shipment, can decline only if the two sets of demand points of the collaborating shippers include the same demand points, that is, if the two shippers have (at least some of) the same customers. Seeking a collaboration partner with the same customers greatly restricts opportunities to collaborate, so we assume in this section that only r reduces as a result of a collaboration with another shipper. Section 5.3.2 includes the case in which β also is reduced.

Let δ_r be the relative reduction of r when transport flows can be combined. Then:

$$\begin{aligned} \overline{c_t}(\alpha) &= \theta \cdot [\beta + (1-\beta) \cdot \alpha^{1-r}]. \\ \underline{c_t}(\alpha) &= \theta \cdot [\beta + (1-\beta) \cdot \alpha^{1-(1-\delta_r)r}]. \\ \Delta c_t(\alpha) &= \overline{c_t}(\alpha) - \underline{c_t}(\alpha) \\ &= \theta \cdot (1-\beta) \cdot \alpha^{1-r} \cdot (1 - \alpha^{\delta_r r}). \end{aligned} \tag{10}$$

Including the per unit transport costs functions $\overline{c_t}(\alpha)$ and $\Delta c_t(\alpha)$ in the total transport costs function, by combining Equations 4 and 10, results in the following total transport costs:

$$TC(x,y) = \mathbb{E}[d(x,y)] \cdot S \cdot N_a \cdot \theta \cdot (\beta + (1-\beta) \cdot \alpha^{1-r} \cdot [1 - P(x,y) \cdot (1 - \alpha^{\delta_r r})]). \tag{11}$$

Theorem 3.2. *Let $0 < \alpha \leq 1$, $0 < \beta \leq 1$, and $0 < r \leq 1$. If we model per distance unit transport costs as a combination of the power and adjusted inverse freight rate functions, the logistics concentration area is the optimal location if and only if:*

$$\mathbb{E}[\Delta d] < \frac{(P_c - P_n) \cdot (1 - k^{-d_{cg}}) \cdot (1-\beta) \cdot \alpha^{1-r} \cdot (1 - \alpha^{\delta_r r})}{\beta + (1-\beta) \cdot \alpha^{1-r} \cdot [1 - P_c \cdot (1 - \alpha^{\delta_r r})]}. \tag{12}$$

Proof. The combination of the power and adjusted inverse freight rate functions results in the following expressions for the total transport cost (difference):

$$\begin{aligned}
TC(x_c, y_c) &= \mathbb{E}[d_c] \cdot S \cdot N_a \cdot \theta \cdot (\beta + (1-\beta) \cdot \alpha^{1-r} \cdot [1 - P(x_c, y_c) \cdot (1 - \alpha^{\delta_r r})]). \\
TC(x_g, y_g) &= \mathbb{E}[d_g] \cdot S \cdot N_a \cdot \theta \cdot (\beta + (1-\beta) \cdot \alpha^{1-r} \cdot [1 - P(x_g, y_g) \cdot (1 - \alpha^{\delta_r r})]). \\
\Delta TC_{cg} &= \frac{\mathbb{E}[d_c] \cdot (\beta + (1-\beta) \cdot \alpha^{1-r} \cdot [1 - P(x_c, y_c) \cdot (1 - \alpha^{\delta_r r})])}{\mathbb{E}[d_g] \cdot (\beta + (1-\beta) \cdot \alpha^{1-r} \cdot [1 - P(x_g, y_g) \cdot (1 - \alpha^{\delta_r r})])} - 1.
\end{aligned} \tag{13}$$

Accordingly, $\Delta TC_{cg} = 0$ if and only if

$$\mathbb{E}[\Delta d] = \frac{[P(x_c, y_c) - P(x_g, y_g)] \cdot (1-\beta) \cdot \alpha^{1-r} \cdot (1 - \alpha^{\delta_r r})}{\beta + (1-\beta) \cdot \alpha^{1-r} \cdot [1 - P(x_c, y_c) \cdot (1 - \alpha^{\delta_r r})]}. \tag{14}$$

From Equations 1 and 14, it follows that the facility will only be located in the logistics concentration area (i.e., $\Delta TC_{cg} < 0$) if and only if Equation 12 holds. □

With Theorem 3.2, each shipper can determine whether it is beneficial to locate in a logistics concentration area, depending on the values of the following firm-specific variables:

- Distance between the logistics concentration area and the center of gravity of customer demand.
- Shipment size.
- Vehicle routing efficiency (with and without cooperation).
- Probability of combining transport flows with the transport flows of other logistics firms in the logistics concentration area (and relative to this probability for a location outside the logistics concentration area).
- Drop costs.

4 The influence of different parameters

Some gains can be obtained from a location in a logistics concentration area, with different values for the different variables. We assume that the logistics concentration area is located within the distribution region. Similar analyses can be conducted outside the distribution region, but they would be less relevant, in that, for example, in just one province of the Netherlands, 19 logistics concentration areas can be identified (Van den Heuvel et al., 2013).

The analysis shows the results for a square-shaped distribution region. Eilon et al. (1971) present expressions for $\mathbb{E}[d(x,y)]$ depending on the shape and size of the region; the effect of the shape of the region on the expected distance to a random customer is small. Because the expression for $\mathbb{E}[d(x,y)]$ in a region with a circular shape would require a hypergeometric function, we prefer using a square region. Similar expressions work for a rectangular region, but require an extra parameter. The difference between $\mathbb{E}[d(x,y)]$ in a circle and a square of the same size is approximately 2%. The difference between $\mathbb{E}[d(x,y)]$ in a rectangle and a square of the same size increases with the ratio of the length of the sides of the region; when this ratio is

Table 2: Full factorial design

		$\Delta TC_{cg} = [TC(x_c, y_c) - TC(x_g, y_g)]/TC(x_g, y_g)$					
Variables	**Values**	**Mean**	**Min.**	**1st quartile**	**Med.**	**3rd quartile**	**Max.**
All		-2.48%	-40.86%	-5.33%	-1.84%	1.40%	8.62%
$d_{cg}/\sqrt{S}$	0.05	-5.96%	-40.86%	-7.86%	-4.55%	-2.53%	0.08%
	0.1	-4.35%	-39.85%	-6.28%	-2.91%	-0.86%	1.79%
	0.15	-1.67%	-38.16%	-3.65%	-0.19%	1.92%	4.65%
	0.2	2.07%	-35.81%	0.01%	3.60%	5.79%	8.62%
α	0.05	-6.55%	-40.86%	-10.66%	-5.32%	-1.28%	8.23%
	0.15	-3.74%	-27.72%	-7.05%	-3.21%	0.13%	8.23%
	0.25	-1.95%	-20.83%	-4.87%	-1.82%	1.35%	8.36%
	0.35	-0.61%	-16.00%	-3.33%	-0.82%	2.42%	8.49%
	0.45	0.47%	-12.24%	-2.13%	0.06%	3.28%	8.62%
r	0.3	0.49%	-19.38%	-2.04%	0.16%	3.40%	8.62%
	0.4	-0.94%	-25.28%	-3.55%	-0.96%	2.28%	8.43%
	0.5	-2.43%	-30.82%	-5.28%	-2.08%	1.12%	8.22%
	0.6	-3.97%	-36.01%	-7.14%	-3.23%	0.09%	8.02%
	0.7	-5.53%	-40.86%	-9.06%	-4.43%	-0.86%	7.80%
δ_r	0.1	0.76%	-15.24%	-1.79%	0.37%	3.57%	8.62%
	0.15	-0.92%	-22.38%	-3.53%	-0.94%	2.30%	8.36%
	0.2	-2.54%	-29.01%	-5.38%	-2.13%	1.07%	8.09%
	0.25	-4.09%	-35.17%	-7.15%	-3.33%	0.01%	7.83%
	0.3	-5.59%	-40.86%	-8.99%	-4.48%	-1.06%	7.57%
$P_c - P_n$	0.3	0.60%	-14.96%	-1.93%	0.24%	3.45%	8.62%
	0.4	-0.63%	-20.14%	-3.23%	-0.70%	2.55%	8.44%
	0.5	-1.86%	-25.32%	-4.62%	-1.63%	1.61%	8.26%
	0.6	-3.09%	-30.50%	-6.01%	-2.53%	0.73%	8.08%
	0.7	-4.33%	-35.68%	-7.55%	-3.49%	-0.07%	7.90%
	0.8	-5.56%	-40.86%	-9.04%	-4.40%	-0.86%	7.72%
β	0	-4.36%	-40.86%	-7.66%	-3.21%	0.25%	8.38%
	0.05	-3.23%	-35.69%	-6.27%	-2.40%	0.83%	8.45%
	0.1	-2.32%	-31.27%	-5.18%	-1.81%	1.40%	8.51%
	0.15	-1.57%	-27.46%	-4.29%	-1.29%	1.95%	8.57%
	0.2	-0.91%	-24.13%	-3.57%	-0.86%	2.40%	8.62%

equal to 1.7, the error is approximately 5%. Finally, $\mathbb{E}[\Delta d]$ is independent of the size of the region S (see the Appendix).

Table 2 shows a full factorial design of all relevant parameters. In a full factorial design, all levels of each independent variable combine with all levels of the other independent variables to produce all possible combinations (for an example, see Hunter and Naylor, 1970). In our case, the table shows the influence of the independent variables $d_{cg}/\sqrt{S}$, α, r, δ_r, $P_c - P_n$, and β on the relative cost difference between a location in the logistics concentration area and the center of gravity of customer demand ΔTC_{cg}. If this difference is negative, the distribution center should locate in the logistics concentration area. To model the rapidly decreasing probability with greater distance from the logistics concentration area, we set k to 10^{100} for the numerical analysis that we present in this section.

The outcomes of a full factorial design depend on the values chosen for the independent variables. The values for the independent variables in Table 2 coincide with those found in prior literature (see Section 3) or are reasonable in practice. We express the distance between the logistics concentration area and the center of gravity of customer demand relative to the size of the region S. In a square region, $\sqrt{S}$ is equal to the length of a side of the region. The included values for $d_{cg}/\sqrt{S}$ reached up to 0.2 times $\sqrt{S}$: the larger this distance, the less attractive the logistics concentration area is. The shipment size, relative to the size of a truck (α), varied between 0.05 and 0.45. Values of $\alpha > 0.5$ decrease possibilities for combining transport flows, because trucks are already more than halfway filled with one shipment. For values of α below 0.05 (i.e., less than a pallet), the shipments are likely offered to couriers, whose standard tariffs are independent of the total transport demand. The variables r and δ_r relate to the per distance unit transportation costs, which depend on the freight rates of the LSP. From prior literature (see Section 3.3), we chose values for r between 0.3 and 0.7. Values of δ were between 10 and 30%. For $P_c - P_n$, which represents the difference between the probabilities of being able to combine transport flows for firms located in and far from the logistics concentration area, we used values between 0.3 and 0.8. With a constant difference between these probabilities, changing the value of P_n (and P_c accordingly) does not result in a major difference in ΔTC_{cg} (increasing P_n from 0 to 0.2 decreases the average ΔTC_{cg} from -2.26% to -2.48%). The difference between these probabilities thus gets included in the analysis. Table 2 shows the results for $P_n = 0.2$. Finally, values for β, representing the drop costs per shipment, varied between 0 and 0.2, in line with prior literature (see Section 3.3).

With these selected values for the different variables, we find on average that it is beneficial to locate in the logistics concentration area, because the average relative difference between the total transportation costs in the logistics concentration area and the center of gravity of customer demand is -2.48% (see Table 2). At their most favorable values, the variables suggest that a gain of 40.86% can be obtained from locating in the logistics concentration area. Starting with the third row of Table 2, we provide ΔTC_{cg} statistics for each value of each variable, compared with all other variables; for example, the third row shows for $d_{cg}/\sqrt{S} = 0.05$ that the average relative gain of locating in the logistics concentration area, rather than a location in the center of gravity of customer demand, is 5.96%. This is the average based on all values of the other five variables (i.e., over $5^4 \cdot 6 = 3750$ values).

These values also show that $d_{cg}/\sqrt{S}$ has the largest influence on ΔTC_{cg}: An increase from 0.05 to 0.2 results in an 8.1 percentage points increase in average ΔTC_{cg}. On average, it is beneficial to locate in the logistics concentration area if this distance is 0.15 times the length of the sides of the distribution region, as we show graphically in Figure 3. In practice, the logistics concentration area can be located up to about 111 kilometers from Orleans (a central city in France) and still be the optimal location for a distribution center that serves customers in France, when we approximate France as a square with 740-km sides.

Also α has a relatively large influence on ΔTC_{cg}, such that an increase of α from the minimum to the maximum value increases the average ΔTC_{cg} by 6.6 percentage points. Table 2 shows that the potential to gain from a location in a logistics concentration area is highest with smaller shipment sizes (within the considered range of shipment sizes).

The variables that relate to the per distance unit transport costs based on the freight rates of the LSP, r and δ_r, have similar influences on the average ΔTC_{cg}, namely, differences of 5.7 and 6.0 percentage

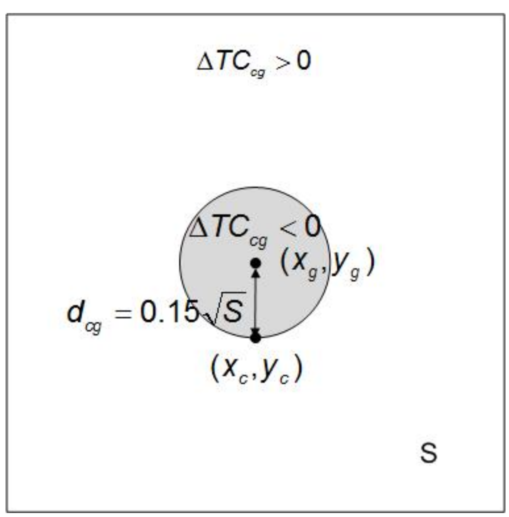


Figure 3: Location in a logistics concentration area within $0.15\sqrt{S}$ units from the center of gravity of customer demand, which is beneficial on average in the cases analyzed with the full factorial design

points, respectively, from their minimum to their maximum values. In practice, the values of r and δ_r are determined by the characteristics of the shipments of the LSP, of the shipper, and of the collaboration partner(s) of the shipper; for example, δ_r is larger when the cost reduction per shipment that the LSP can obtain by combining shipments of the collaborating shippers is larger. In general, adding the shipments of the collaborating shippers lowers the costs for the LSP and thereby lowers freight rates in two ways: First, the number of shipments of the collaborating shippers is relatively large compared with the number of shipments by the LSP's other customers, such that adding these shipments results in a much higher network density. Second, the shipments of the collaborating shippers complement the shipments of the LSP, such as by adding return trips to the trips the LSP already had planned.

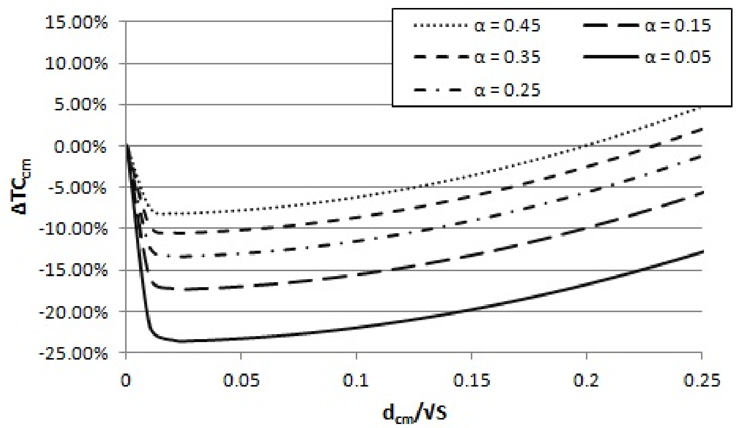
The difference between the probabilities of combining transport flows ($P_c - P_n$) and the drop costs β results in a decrease of the average ΔTC_{cg} by 4.8 and 3.2 percentage points, respectively, if changed from the minimum to the maximum allowed value. That is, these variables have the least influence on ΔTC_{cg} of all the variables we have considered.

For additional insights, Table 3 lists statistics similar to those in Table 2, but with specific values for the two most important variables, $d_{cg}/\sqrt{S}$ and α. For relatively high values of these variables, it is not beneficial to locate in the logistics concentration area. Instead, locating in the logistics concentration area is beneficial on average only if the distance between the logistics concentration area and the center of gravity of customer demand is less than 0.2 times the length of the sides of the region and the shipment size is 5% of a full truck, or else if the distance is less than 0.15 times the length of the sides of the region, even for shipments whose sizes are less than 25% of a full truck. With $d_{cg}/\sqrt{S} = 0.15$, in 25% of the cases, it even remains beneficial to locate in the logistics concentration area for $\alpha \leq 0.35$.

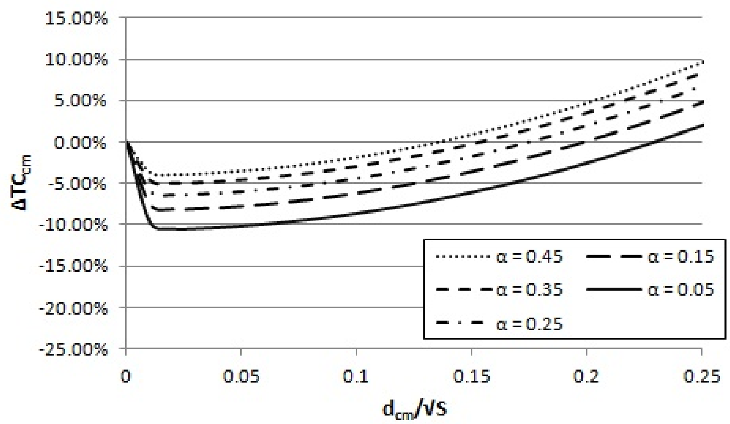
Finally, in Figure 4 we depict the relationship between $d_{cg}/\sqrt{S}$ and ΔTC_{cg} for different values of α, r, and δ_r, with the other variables fixed at their median (from Table 2). For the median values of r and δ_r, Figure 4(b) shows that the combination of $d_{cg}/\sqrt{S}$ and α determines whether it is beneficial to locate in the logistics concentration area and the size of the benefits. A comparison of Figures 4(a) to 4(c) shows that the product of δ_r and r exerts a major influence on the benefits obtained from a location in the logistics concentration area: If this product is small (Figure 4(c)), there is (almost) no benefit of locating in the logistics concentration area, but if this product is relatively large (Figure 4(a)), large gains result from

Table 3: Full factorial design for specific values of $d_{cg}/\sqrt{S}$ and α

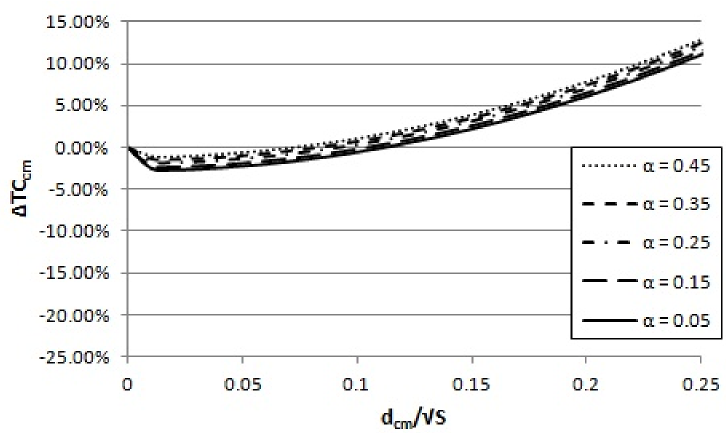
		$\Delta TC_{cg} = [TC(x_c, y_c) - TC(x_g, y_g)]/TC(x_g, y_g)$					
$d_{cg}/\sqrt{S}$	α	**Mean**	**Min.**	**1st quartile**	**Med.**	**3rd quartile**	**Max.**
0.05	0.05	-9.89%	-40.86%	-13.25%	-8.13%	-4.71%	-0.28%
0.05	0.15	-7.18%	-27.72%	-9.66%	-6.06%	-3.61%	-0.29%
0.05	0.25	-5.45%	-20.83%	-7.37%	-4.64%	-2.75%	-0.17%
0.05	0.35	-4.16%	-16.00%	-5.61%	-3.54%	-2.08%	-0.04%
0.05	0.45	-3.12%	-12.24%	-4.27%	-2.65%	-1.48%	0.08%
0.1	0.05	-8.35%	-39.85%	-11.76%	-6.56%	-3.07%	1.43%
0.1	0.15	-5.58%	-26.48%	-8.11%	-4.44%	-1.96%	1.42%
0.1	0.25	-3.83%	-19.47%	-5.78%	-3.00%	-1.08%	1.54%
0.1	0.35	-2.52%	-14.56%	-3.99%	-1.88%	-0.40%	1.67%
0.1	0.45	-1.46%	-10.74%	-2.63%	-0.98%	0.20%	1.79%
0.15	0.05	-5.78%	-38.16%	-9.29%	-3.94%	-0.36%	4.27%
0.15	0.15	-2.94%	-24.42%	-5.53%	-1.77%	0.79%	4.26%
0.15	0.25	-1.14%	-17.21%	-3.14%	-0.28%	1.69%	4.39%
0.15	0.35	0.21%	-12.16%	-1.30%	0.87%	2.39%	4.52%
0.15	0.45	1.30%	-8.24%	0.10%	1.80%	3.01%	4.65%
0.2	0.05	-2.20%	-35.81%	-5.84%	-0.29%	3.43%	8.23%
0.2	0.15	0.75%	-21.55%	-1.94%	1.97%	4.62%	8.23%
0.2	0.25	2.62%	-14.07%	0.54%	3.50%	5.56%	8.36%
0.2	0.35	4.02%	-8.83%	2.45%	4.70%	6.28%	8.49%
0.2	0.45	5.15%	-4.75%	3.90%	5.67%	6.93%	8.62%



(a) $r = 0.7$, $\delta_r = 0.3$, $\delta_r r = 0.21$



(b) $r = 0.5$, $\delta_r = 0.2$, $\delta_r r = 0.10$



(c) $r = 0.3$, $\delta_r = 0.1$, $\delta_r r = 0.03$

Figure 4: ΔTC_{cg} as a function of $d_{cg}/\sqrt{S}$ and different values of α ($P_n = 0.2, P_c = 0.8, \beta = 0.1$)

locating in the logistics concentration area. Recall that Table 2 showed that δ_r and r have an comparable individual influences on the total cost difference.

In conclusion, a location in the logistics concentration area is beneficial on average if the distance between the logistics concentration area and the center of gravity of customer demand is less than 0.2 times the length of the sides of the region and the shipment size is 5% of a full truck, or if this distance is less than 0.15 times the length of the sides of the region, even for shipment sizes of less than 25% of a full truck. However, the benefits of co-location depend on six different variables, so each specific situations must determine whether a location in the logistics concentration area will be beneficial for each specific shipper. We recommend that shippers use Equation 5 to determine the benefits they are likely to gain from locating in a logistics concentration area in each situation they encounter in practice.

5 Model extensions

This section relaxes some of the assumptions in Section 3 and presents some extensions to the model.

5.1 Demand per customer greater than one truck

We previously assumed that the demand per customer is smaller than the capacity of a truck, such that all customers could be served solely with round trips. In practice, demand per customer may exceed the capacity of a truck, in which case customer demand can be divided into $N_w = \lfloor \frac{v}{W} \rfloor \in \mathbb{N}$ full truck loads and some fraction of partial truckloads $0 \leq \alpha_w = \frac{v}{W} - N_w < 1$. The transport costs per distance unit per period c_t change with the costs of the full truck loads:

$$\begin{array}{lcl} \overline{c_t}(N_w, \alpha_w) & = & \theta N_w + \overline{c_t}(\alpha_w), \\ \underline{c_t}(N_w, \alpha_w) & = & \theta N_w + \underline{c_t}(\alpha_w), \text{ and} \\ \Delta c_t(N_w, \alpha_w) & = & \Delta c_t(\alpha_w). \end{array} \tag{15}$$

The logistics firm is indifferent between a location in the logistics concentration area and in the center of gravity of customer demand if and only if:

$$\mathbb{E}[\Delta d] = \frac{(P_c - P_n) \cdot (1 - k^{-d_{cg}}) \cdot \Delta c_t(\alpha_w)}{\theta N_w + \overline{c_t}(\alpha_w) - P_c \cdot \Delta c_t(\alpha_w)}, \tag{16}$$

and with the combined per distance unit transport cost function:

$$\mathbb{E}[\Delta d] = \frac{(P_c - P_n) \cdot (1 - k^{-d_{cg}}) \cdot (1 - \beta) \cdot \alpha_w^{1-r} \cdot (1 - \alpha^{\delta_r r})}{N_w + \beta + (1 - \beta) \cdot \alpha_w^{1-r} \cdot (1 - P_c \cdot (1 - \alpha^{\delta_r r}))}. \tag{17}$$

The number of full trucks to be delivered per customer N_w strongly influences whether a location in the logistics concentration area is beneficial or not. A location outside the center of gravity of customer demand results in many extra units of transport distance if many trucks are needed per customer.

5.2 More than one logistics concentration area

The model in Section 3 assumed only one logistics concentration area in the region. In practice, there probably are more than one (e.g., Van den Heuvel et al., 2013). These different logistics concentration areas also should have different characteristics. Van den Heuvel et al. (2012a) distinguish between specialized and diverse logistics concentration areas, such that the former contain logistics firms with a similar specialization based on sector, product type, and/or service, whereas the latter contain many different logistics firms without any particular specialization. Van den Heuvel et al. (2012a) conclude that logistics firms located in specialized logistics concentration areas for fresh produce exchange more transport capacity than logistics firms in diverse logistics concentration areas. Accordingly, for logistics firms that specialize in the storage and transport of fresh produce, the probability of combining transport flows with other logistics firms is higher in a specialized logistics concentration area rather than in a diverse logistics concentration area. Furthermore, the potential for cooperation with other firms may be higher, because these firms likely have a similar distribution of customers over the region.

Assume that the region described in Section 3 contains two logistics concentration areas, c_1 and c_2. Furthermore, assume $P_{c_1} > P_{c_2} > P_n$ and $\Delta c_{t,c_1} > \Delta c_{t,c_2}$. The probability of combining transport flows and/or the related gains could be greater in one logistics concentration area than in the other for several reasons, such as a relevant specialization. In turn, we can identify three possibly optimal facility locations in this region, depending on the distances between these logistics concentration areas and the center of gravity of customer demand. If c_1 is closer to the center of gravity of customer demand than c_2 is, then c_2 no longer is an interesting location, because $\mathbb{E}[d(x_{c_1}, y_{c_1})] < \mathbb{E}[d(x_{c_2}, y_{c_2})]$. However, if c_2 is closer to this center of gravity than c_1, we confront the same trade-off between the extra benefits and the extra units of transport distance resulting from a location in logistics concentration area 1. To be indifferent between the two logistics concentration areas, transport costs must be equal, $TC(x_{c1}, y_{c1}) = TC(x_{c2}, y_{c2})$, which occurs if and only if:

$$\frac{\mathbb{E}[d(x_{c_1}, y_{c_1})]}{\mathbb{E}[d(x_{c_2}, y_{c_2})]} = \frac{\overline{c_t}(\alpha) - P_{c_2} \cdot \Delta c_{t,c_2}}{\overline{c_t}(\alpha) - P_{c_1} \cdot \Delta c_{t,c_1}}, \tag{18}$$

and according to the combined per distance unit transportation cost function ($\delta_{r,c_1} > \delta_{r,c_2}$):

$$\frac{\mathbb{E}[d(x_{c_1}, y_{c_1})]}{\mathbb{E}[d(x_{c_2}, y_{c_2})]} = \frac{\beta + (1-\beta) \cdot \alpha^{1-r} \cdot (1 - P_{c_2} \cdot (1 - \alpha^{\delta_{r,c_2} r}))}{\beta + (1-\beta) \cdot \alpha^{1-r} \cdot (1 - P_{c_1} \cdot (1 - \alpha^{\delta_{r,c_1} r}))}. \tag{19}$$

By comparing the two logistics concentration areas, we can determine which is more cost-efficient. The logistics concentration area with lower costs then can be compared against the center of gravity of customer demand, using the model in Section 3. An analysis with more than two logistics concentration areas can be conducted similarly.

5.3 Other per distance unit transport cost function

We previously modeled the per distance unit transport costs using a combination of the power and adjusted inverse freight rate function, with the costs normalized on the full truckload freight rate. Gains in horizontal collaboration only resulted in an increase of the routing efficiency. These assumptions are relaxed in this section.

5.3.1 Full truck rates for LTL shipments

We previously assumed that transporting shipments smaller than a TL shipment ($\alpha < 1$) always costs less than a full truckload θ. However, in practice, freight rate tables may include a category from about 70% of a truck until a TL with a constant freight rate (e.g., Mendoza and Ventura, 2009). If so, then the per distance unit cost function should be normalized not on a full truck (as in Section 3) but on about 70% of a full truck. If we define z as the shipment size relative to the truck size from which a full truckload rate is paid, we obtain the following per distance unit transport cost (difference) functions (for $\alpha < z$):

$$\begin{aligned} \overline{c_t}(\alpha) &= \theta \cdot [\beta + (1-\beta) \cdot z^{r-1} \cdot \alpha^{1-r}], \\ \underline{c_t}(\alpha) &= \theta \cdot [\beta + (1-\beta) \cdot z^{(1-\delta_r)r-1} \cdot \alpha^{1-(1-\delta_r)r}], \\ \Delta c_t(\alpha) &= \theta \cdot (1-\beta) \cdot z^{r-1} \cdot \alpha^{1-r} \cdot (1 - z^{-\delta_r r} \cdot \alpha^{\delta_r r}). \end{aligned} \tag{20}$$

Figure 5 shows the meaning of z graphically. With analyses similar to those we conducted in Section 4, we considered z values ranging from 0.7 to 1 (in increments of 0.1). Because decreasing z increases the per distance unit cost function (see Figure 5), we also decreased r to compensate, such that the r values ranged from 0.2 to 0.6. With decreasing z from 1 to 0.7, the average total transportation cost difference ΔTC_{cg} values were equal to -1.00%, -0.71%, -0.38%, and 0.01%, respectively. That is, a lower z implied a less attractive location in a logistics concentration area. Table 4 presents the full factorial design with z equal to 0.7. Comparing Tables 2 and 4 reveals that though the benefits of locating in a logistics concentration area generally decreased, in slightly less than 50% of the cases (based on the median shown in the second row of Table 4), the location in a logistics concentration area still was optimal.

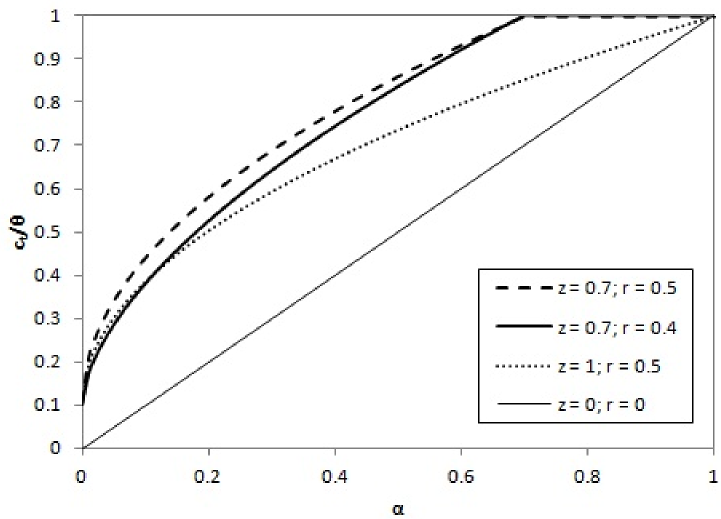


Figure 5: Transport costs per distance unit as function of z and r

5.3.2 Partner has same customers

Section 3 assumed that cooperation would decrease r in the per distance unit transport cost function. However, if the cooperation partner has at least some of the same customers, the drop costs β also decrease, resulting in different (per distance unit) transport costs (difference) functions. In practice, this is especially relevant for supply to retail, as many suppliers only supply a relatively small number of retailers, such that they all probably have some of the same customers.

We define δ_β as the relative decrease of β that results from an overlap of customers of the shipper and its collaboration partner(s). Then, the cost functions change to:

$$\begin{array}{rcl} \underline{c_t}(\alpha) & = & \theta \cdot [(1-\delta_\beta) \cdot \beta + (1-(1-\delta_\beta)\cdot\beta) \cdot \alpha^{1-(1-\delta_r)r}], \\ \Delta c_t(\alpha) & = & \theta \cdot [(1-\beta)\cdot\alpha^{1-r}\cdot(1-\alpha^{\delta_r r}) + \delta_\beta \cdot \beta \cdot (1-\alpha^{1-(1-\delta_r)r})] \\ TC(x,y) & = & \mathbb{E}[d(x,y)] \cdot S \cdot N_a \cdot \theta \cdot (\beta + (1-\beta)\cdot\alpha^{1-r}\cdot[1-P(x,y)\cdot(1-\alpha^{\delta_r r})], \\ & & -P(x,y)\cdot\delta_\beta\cdot\beta\cdot(1-\alpha^{1-(1-\delta_r)r})). \end{array} \tag{21}$$

Without replicating the full factorial design, it is clear that if both r and β can be reduced by choosing a location in a logistics concentration area, logistics concentration areas only become more attractive.

5.4 Continuous facility location model

Analytic facility location models assume that customers are distributed continuously across the service region, whereas continuous location models assume that demands arise only at discrete locations (though the facility can be located anywhere in the region; for precise definitions of facility location models, see Daskin, 2008). If, instead of relying on the assumptions of an analytic facility location model, we assume that demands arise at discrete locations (from customers who we still assume are similar), the total transport costs can be expressed as follows, where $d_i(x,y)$ is the distance between customer i and the facility at location (x,y), and $n = N_a \cdot S$ is the total number of customers:

$$\begin{array}{rcl} TC(x,y) & = & \sum_{i=1}^{n}(1-P(x,y))\cdot\overline{c_t}(\alpha)\cdot d_i(x,y) + P(x,y)\cdot\underline{c_t}(\alpha)\cdot d_i(x,y) \\ & = & [\overline{c_t}(\alpha) - P(x,y)\cdot\Delta c_t(\alpha)]\sum_{i=1}^{n} d_i(x,y). \end{array} \tag{22}$$

The location decision maker is indifferent between a location in the center of gravity of customer demnad (x_g, y_g) and the logistics concentration area (x_c, y_c) if and only if (similar to Equation 8):

$$\frac{\sum_{i=1}^{n} d_i(x_c,y_c) - d_i(x_g,y_g)}{\sum_{i=1}^{n} d_i(x_g,y_g)} = \frac{\Delta c_t(\alpha)\cdot(P_c - P_n)\cdot(1-k^{-d_{cg}})}{\overline{c_t}(\alpha) - P_c\cdot\Delta c_t(\alpha)}. \tag{23}$$

Table 4: Full factorial design with $z = 0.7$

Variables	Values	$\Delta TC_{cg} = [TC(x_c, y_c) - TC(x_g, y_g)]/TC(x_g, y_g)$					
		Mean	**Min.**	**1st quartile**	**Med.**	**3rd quartile**	**Max.**
All		0.01%	-32.34%	-2.45%	0.05%	3.45%	8.95%
$d_{cg}/\sqrt{S}$	0.05	-3.56%	-32.34%	-4.72%	-2.38%	-1.05%	0.38%
	0.1	-1.91%	-31.18%	-3.09%	-0.71%	0.64%	2.1%
	0.15	0.84%	-29.25%	-0.37%	2.07%	3.46%	4.96%
	0.2	4.67%	-26.56%	3.41%	5.95%	7.40%	8.95%
α	0.05	-3.49%	-32.34%	-6.92%	-2.69%	0.73%	8.61%
	0.15	-1.09%	-19.90%	-3.90%	-1.04%	2.19%	8.63%
	0.25	0.46%	-13.51%	-2.16%	0.07%	3.34%	8.74%
	0.35	1.62%	-9.09%	-1.02%	1.08%	4.16%	8.85%
	0.45	2.55%	-5.67%	-0.22%	1.74%	4.73%	8.95%
r	0.2	2.29%	-11.56%	-0.38%	1.60%	4.61%	8.95%
	0.3	1.19%	-17.19%	-1.31%	0.81%	4%	8.84%
	0.4	0.05%	-22.52%	-2.5%	-0.09%	3.24%	8.73%
	0.5	-1.13%	-27.57%	-3.86%	-0.88%	2.41%	8.62%
	0.6	-2.34%	-32.34%	-5.28%	-1.70%	1.54%	8.5%
δ_r	0.1	2.09%	-11.56%	-0.5%	1.48%	4.53%	8.95%
	0.15	1.02%	-17.19%	-1.45%	0.71%	3.92%	8.84%
	0.2	-0.02%	-22.52%	-2.52%	-0.08%	3.26%	8.74%
	0.25	-1.03%	-27.57%	-3.67%	-0.76%	2.56%	8.63%
	0.3	-2.01%	-32.34%	-4.76%	-1.40%	1.82%	8.53%
$P_c - P_n$	0.3	1.96%	-11.77%	-0.61%	1.41%	4.47%	8.95%
	0.4	1.18%	-15.88%	-1.33%	0.84%	4.03%	8.88%
	0.5	0.40%	-20.00%	-2.11%	0.22%	3.56%	8.81%
	0.6	-0.38%	-24.11%	-2.96%	-0.34%	3.06%	8.74%
	0.7	-1.16%	-28.22%	-3.82%	-0.80%	2.50%	8.67%
	0.8	-1.94%	-32.34%	-4.72%	-1.29%	1.95%	8.60%
β	0	-1.22%	-32.34%	-3.89%	-0.66%	2.63%	8.87%
	0.05	-0.47%	-27.71%	-3.05%	-0.27%	3.11%	8.89%
	0.1	0.12%	-23.89%	-2.37%	0.07%	3.46%	8.91%
	0.15	0.60%	-20.68%	-1.89%	0.43%	3.76%	8.93%
	0.2	1.02%	-17.94%	-1.45%	0.74%	3.94%	8.95%

Because we model every customer separately, we now can consider different levels of demand per customer. Furthermore, the model in Section 3 assumed that for every customer, the probability of a combined delivery was the same, depending on the location of the distribution center. This assumption may be reasonable if customers are uniformly distributed over the region. However, if demands arise at discrete points in the region, for some customers, delivery might be combined with deliveries from other logistics firms; for other firms, delivery simply cannot be combined, depending primarily on the location of the customer. That is, if the customer is located close to other firms, transport to that customer likely can be combined with transport from other firms. If the customer instead has an isolated location, there is no gain from combining its demand with another firm's transport flows. Therefore, the probability that transport flows can be combined depends on the location of not only the facility but also the customer i. Finally, the per distance unit transport cost function may depend on the customer (location). Then, total transport costs can be expressed as follows:

$$TC(x,y) = \sum_{i=1}^{n} [\overline{c_{t,i}}(\alpha_i) - P_i(x,y) \cdot \Delta c_{t,i}(\alpha_i)] \cdot d_i(x,y). \tag{24}$$

Although this model can be analyzed in general, it primarily is valuable for specific situations in practice, because the outcomes depend on specific customer characteristics.

6 Conclusions

We have developed a model to determine the optimal location of a distribution center by explicitly taking into account the opportunity to combine transport flows in logistics concentration areas. Traditional facility location models only model transport costs from the perspective of the shipper's supply chain, whereas our proposed model includes a transport cost function that depends on opportunities to combine transport flows with other shippers. This opportunity is location dependent and is higher when there are more other shippers in close proximity to the shipper's location. A location in a logistics concentration area thus provides an excellent opportunity to decrease transport costs by combining transport flows with other shippers' transport flows. At the same time, logistics concentration areas may not appear co-located with the center of gravity of customer demand, such that the distances that need to be traveled tend to increase. The trade-off between reduced transport costs and the extra distance traveled determines whether it is optimal to locate in a logistics concentration area. This trade-off primarily depends on the distance between the logistics concentration area and customer demand, together with the average shipment size. In addition, the combination of the current routing efficiency and the improvement that can be obtained from collaboration offers another important variable for determining whether the logistics concentration area is the optimal location for a distribution center.

A shipper can use the model we have developed to determine whether a location in a logistics concentration is optimal, based on the transportation costs resulting from the location decision. Numerical experiments based on a square-shaped distribution region show that on average it is beneficial to locate in the logistics concentration area, if that area is within a distance of 0.15 times the length of the sides of the region from the center of gravity of customer demand. In addition, for relevant shipment sizes (i.e., between 5% and 50% of the capacity of a full truck), smaller shipments increase the probable gains from locating in a logistics concentration area. Recent developments such as just-in-time manufacturing and e-commerce, have radically altered supply chains (Johnson and Whang, 2002), resulting in smaller shipment sizes in general (Hesse, 2002; Banister and Stead, 2004; Janssen and Verbraeck, 2005), which increases the attractiveness of logistics concentration areas. This development also may explain the increased attention to logistics clusters (Sheffi, 2012) and why logistics concentration areas grow over time (e.g., in the south of the Netherlands, Van den Heuvel et al., 2013). Because the exact cost advantage of locating in a logistics concentration area also depends on transportation efficiency, the difference in the probability of combining transport flows in a logistics concentration area versus elsewhere, and the drop costs, individual shippers should use our model to determine whether a location in a logistics concentration area really is beneficial for their specific situations.

This article presents a novel model that explicitly considers synergies achieved through the co-location of logistics firms in a shipper's location decision. Using an analytic facility location model, we assumed uniformly distributed demand points over the region and equal deterministic demand from each customer. Extending this approach to discrete location decision models aqnd/or stochastic models offers an interesting route for further research and could result in additional insights for firms that must determine the optimal location for a new distribution center.

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Appendix

Expected distance between the facility and a random customer

The expected distance between the center of gravity of customer demand (x_g, y_g) and a random customer in a region with the shape of a square (Eilon et al., 1971) is equal to:

$$
\begin{aligned}
\mathbb{E}[d_g] &= \mathbb{E}[d(\tfrac{1}{2}\sqrt{S}, \tfrac{1}{2}\sqrt{S})] \\
&= \tfrac{1}{6S}\left[4\cdot\left(\tfrac{1}{2}S\right)^{\frac{3}{2}} + 4\cdot\left(\tfrac{1}{2}\sqrt{S}\right)^{3}\ln\left(\frac{\tfrac{1}{2}\sqrt{S}+\sqrt{\tfrac{1}{2}S}}{-\tfrac{1}{2}\sqrt{S}+\sqrt{\tfrac{1}{2}S}}\right)\right] \\
&= \frac{\sqrt{S}}{12}\left[2\sqrt{2}+\ln\left(3+2\sqrt{2}\right)\right].
\end{aligned}
\tag{25}
$$

The expected distance between the logistics concentration area (x_c, y_c) and a random customer can be expressed relative to the center of gravity of customer demand, with $-0.5 \leq \Delta x = x_c/\sqrt{S} - 0.5 \leq 0.5$ and $-0.5 \leq \Delta y = y_c/\sqrt{S} - 0.5 \leq 0.5$:

$$
\begin{aligned}
\mathbb{E}[d_c] &= \mathbb{E}[d(\tfrac{1}{2}\sqrt{S}+\Delta x\sqrt{S}, \tfrac{1}{2}\sqrt{S}+\Delta y\sqrt{S})] \\
&= \tfrac{\sqrt{S}}{6}\Big[2CD\sqrt{C^2+D^2}+2CF\sqrt{C^2+F^2}+2ED\sqrt{E^2+D^2}+2EF\sqrt{E^2+F^2} \\
&\quad +C^3\ln\left(\frac{D+\sqrt{C^2+D^2}}{-F+\sqrt{C^2+F^2}}\right)+D^3\ln\left(\frac{C+\sqrt{C^2+D^2}}{-E+\sqrt{E^2+D^2}}\right) \\
&\quad +E^3\ln\left(\frac{D+\sqrt{E^2+D^2}}{-F+\sqrt{E^2+F^2}}\right)+F^3\ln\left(\frac{C+\sqrt{C^2+F^2}}{-E+\sqrt{E^2+F^2}}\right)\Big]
\end{aligned}
\tag{26}
$$

where

$$
C = \tfrac{1}{2}-\Delta x \qquad D = \tfrac{1}{2}-\Delta y \qquad E = \tfrac{1}{2}+\Delta x \qquad F = \tfrac{1}{2}+\Delta y
$$

Dividing Equation 25 by Equation 26 leaves an expression independent of S.

List of variables

α	=	Shipment size as a fraction of a full truckload (per customer per period)
α_w	=	Fraction of a full truckload remaining after the full truckloads are subtracted from the shipment size (per period)
β	=	Shape parameter of the adjusted inverse freight rate function
$c_t(\alpha)$	=	Transport costs depending on the shipment size α (Euro per distance unit per period)
$\overline{c_t}(\alpha)$	=	Transport costs depending on the shipment size α if flows can be combined with other logistics companies (Euro per distance unit per period)
$\underline{c_t}(\alpha)$	=	Transport costs depending on the shipment size α if flows cannot be combined with other logistics companies (Euro per distance unit per period)
$d_c(x,y)$	=	Distance between the logistics concentration area and the distribution center at location (x,y) (distance units)
d_{cg}	=	Distance between the logistics concentration area and the center of gravity of customer demand (distance units)
$\Delta c_t(\alpha)$	=	Difference between the per distance unit transport costs in case flows can be combined and the transport costs in case flows cannot be combined (Euro per distance unit per period)
ΔTC_{cg}	=	Relative total transport cost difference between the location in the logistics concentration area and the center of gravity of customer demand
δ_β	=	Relative reduction of β if flows can be combined
δ_r	=	Relative reduction of r if flows can be combined
$\mathbb{E}[d(x,y)]$	=	Expected distance between the distribution center at location (x,y) and a random customer in the distribution region (distance units)
$\mathbb{E}[d_c]$	=	$\mathbb{E}[d(x_c,y_c)]$
	=	Expected distance between the distribution center in the logistics concentration area and a random customer in the distribution region (distance units)
$\mathbb{E}[d_g]$	=	$\mathbb{E}[d(x_g,y_g)]$
	=	Expected distance between the distribution center in the center of gravity of customer demand and a random customer in the region (distance units)

$\mathbb{E}[\Delta d]$	=	Expected extra transport distance to a random customer in the region resulting from a location in the logistics concentration area relative to the location in the center of gravity of customer demand (distance units)
$f_t(v)$	=	Freight rate depending on the shipment size v (Euro per weight unit per distance unit)
k	=	Shape parameter of the probability function
N_a	=	Spatial customer density (number of customers per squared distance unit)
N_w	=	Number of full truckloads per shipment (per period)
$P(x, y)$	=	Probability that transport flows can be combined at location (x, y)
P_c	=	Probability that transport flows can be combined in the logistics concentration area
P_n	=	Probability that transport flows can be combined at a location far from the logistics concentration area
r	=	Shape parameter of the power freight rate function
S	=	Size of the distribution region (squared distance units)
$TC(x, y)$	=	Total transport costs resulting from a location in (x, y) (Euro per period)
θ	=	Transport costs of a TL shipment (Euro per distance unit per period)
v	=	Shipment size (weight units per customer per period)
W	=	Weight of a TL shipment (weight units)
z	=	Shipment size as a fraction of a full truck from which a full truckload is paid

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