

The 9th International Conference on City Logistics, Tenerife, Canary Islands (Spain), 17-19 June 2015

## An evaluation of urban consolidation centers through continuous analysis with non-equal market share companies

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### Abstract

This paper analyzes the logistic cost savings caused by the implementation of Urban Consolidation Centers (UCC) in a dense area of a city. In these urban terminals, freight flows from interurban carriers are consolidated and transferred to a neutral last-mile carrier to perform final deliveries. This operation would reduce both last-mile fleet size and average distance cost. Our UCC modeling approach is focused on continuous analytic models for the general case of carriers with different market shares. Savings are highly sensitive to the design of the system: the increment of capacity in interurban vehicles and the proximity of the UCC terminal to the area in relation to current distribution centers. An exhaustive collection of possible market shares distributions are discussed. Results show that market shares distribution does not affect cost savings significantly. The analysis of the proposed model also highlights the trade-off between savings in the system and a minimum market share per company when the consolidation center is established.

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Peer-review under responsibility of the organising committee of the 9th International Conference on City Logistics

*Keywords:* Urban consolidation center; analytic mathematical model; logistics; urban freight transport

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### 1. Introduction

Urban goods distribution is indispensable for the economic development of cities but it contributes to the worsening of several issues related to traffic congestion and the environment. Stakeholders of urban systems are affected in some

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way by these problems. On the one hand, carriers spend most part of their time (up to a 28% of overall logistics costs) in last-mile distribution due to the increasing levels of traffic congestion, lack of unloading/loading zones, and other inefficiencies (Goodman, 2005; ASCE, 1998). On the other hand, urban citizens often undergo environmental effects like pollution, noise, or space competition. Furthermore, the carrier's customers become more and more demanding in terms of time windows, frequency and competitive prices.

The problem of establishing effective operative measures to improve urban distribution is a challenge because it arises in the context of a heterogeneous market with multiple types of products, roles, and conflicting objectives. Even if urban distribution causes great inconveniences in most cities, there is usually a lack of guidelines or leadership from the local authorities to regulate and organize distribution in order to make it more efficient. Thus, there is a special need for innovative solutions, both involving public and private parties, to be able to generate attractive benefits for both, companies and urban citizens (McKinnon, 2008).

In this paper we will propose a strategic solution that entails cooperation between freight carriers for the common use of a public freight terminal located near the distribution area. The main idea behind our approach is to schedule urban distribution in two separate phases. The first one takes place during certain time periods (preferably at night), when carriers from all companies bring their goods to an Urban Consolidation Center (UCC). The second phase takes place during the day, when a neutral freight carrier performs, jointly for all companies, local delivery in the areas with higher customer density. Such a system implies several advantages with respect to a system without a UCC in which each carrier is responsible for distributing its goods to all its customers. In the first phase, the system allows transport operators to use larger vehicles to bring their load to the UCC with fewer time restrictions. Furthermore, the last mile's negative effects of the second phase are also considerably reduced since local deliveries are performed more efficiently and with less environmental impact due to the consolidation of goods.

### *1.1. Literature Review*

Several contributions exist in the literature related to our work. Roca-Riu et al. (2012) presents a model to estimate distribution costs in an urban area under a simplifying assumption: the equal market share among transport companies. Systems of a similar nature to the one we propose which allow different market shares, are presented in Köhler (2001) or Ieda (2010), who describe specific implementations of UCC systems in German cities or in Japan respectively. These results apply to each case study, but no general analysis is included and therefore it is difficult to extrapolate the results. Saberi et al. (2012) presents a similar approach in the continuous model of general applicability, but its focus is to minimize emissions at the strategic level.

There are other published works presenting models that analyze the effects of collaborative strategies in urban distribution. Kawamura and Lu (2008) follows a methodology with points in common to the one we use, although their modelling hypotheses, which are somehow different from ours, have been adapted to an urban-interurban American context. In particular, some of the modelling hypotheses they consider are: holding costs, the adjustment of the frequency of dispatch, and that big trucks may enter the city without problems. Rarely do such hypotheses and context values hold for the dense urban contexts of many European cities. Later in 2012, Chen et al. (2012) presents a more general model including the European context in terms of customer density, facility location or vehicle type. However, modelling hypotheses differences remain. Moreover, it is assumed that all transport companies serve all customers, which seems unrealistic from a practical point of view. In contrast, our approach encompasses any market distribution among companies. Furthermore, we also address the non-homogeneous demand case.

A totally different approach to analyse collaboration strategies has been followed in (Krajewska and Kopfer, 2006; Krajewska et al. 2008), who address the cost allocation problem. This problem studies the distribution of new costs and its benefits due to the collaborative process among participants. The methodological framework of this approach considers both combinatorial auctions and operational research game theory. Indirectly, they use collaboration models to obtain data for cost allocations.

### 1.2. Objectives and contributions

The main purpose of this paper is to quantify the operational effects of the implementation of a UCC in a general context of carriers with different market shares. Several questions are addressed: i) under what circumstances is the UCC globally beneficial for all the parties involved; ii) what is the potential performance of a system with a UCC for an exhaustive collection of possible market share distributions; and, iii) to what extent can an individual company that joins a UCC system affect the overall savings.

The new contributions overcome some drawbacks of previously presented papers. Our analysis is based on the study of an analytic model, Logistics System Analysis, (Daganzo, 2005), which determines accurate approximations of all the costs involved. This is a general approach that can be used in different cities or contexts by only adapting some local parameters.

We overrule the equal market share assumption of Roca-Riu et al. (2012) and allow different market share structures between carriers. Examples can be found of heterogeneous markets where the equal market share assumption does not apply. For instance, data collected from the Spanish Institute of Statistics (INE, 2009) illustrates the heterogeneity of the Spanish market with over 200,000 transport companies, mostly with a small number of workers.

The other main contribution is a tool to regulate the participation of many carriers to the UCC. Due to a highly competitive market, a system with a UCC could be objected by medium-size and large carriers. The reason that large carriers could have to limit the participation of very small carriers is that small carriers do not significantly increase the number of customers, but are greatly benefitted from the consolidation center. We present a new tool to determine a threshold on the minimum demand of a company to join the UCC.

### 1.3. Paper overview

The models used in our analysis are presented in the Methodology section. In the first part of the next section we recall the model of Roca-Riu et al. (2012), with the equal market share assumption. We use this model to introduce most of the notation that we will use later on and to illustrate an application of the methodology of the Logistic System Analysis (Daganzo, 2005). Then, we will introduce our new model for the general case of carriers with different market shares, whereas in the following section we will analyze the proposed model for an exhaustive collection of possible market share distributions. Results indicate that collaboration among carriers through a UCC may reduce the overall operational costs. In the last subsection of the Methodology, we will model the trade-off between the participation of small carriers and its contribution to the savings of the UCC. The model can be used to determine a threshold on the minimum demand of a company to produce minimum desired savings in the operation costs of the consolidation center system. Finally, in the following section we will present and discuss our main results in depth. The paper ends with some conclusions and comments about future research.

## 2. Methodology

In this section we present the different models that are used to compare the performance of urban distribution systems with and without UCCs. We base our analysis on a continuous approximation model providing robust solutions. It highlights trends in a sensitivity analysis and gives us additional insights into the solutions for the case of different market share companies. Our new main model determines the optimal distribution strategy for non-equal market share companies using a consolidation center, when customers are spread over a delimited area.

### 2.1. Optimal distribution strategy for a single company

Based in Roca-Riu et al. (2012), this model finds the optimal strategy that a single company should use to serve its clients spread throughout an area and its main performance metrics.

In urban goods distribution, several service areas may exist but in this paper it is assumed that operation is independent in each of them. Then, we can just consider one single service area. Vehicles depart from a given depot and travel to the service area where they perform their local delivery with their fleet and then return to the depot.

For a given service area, the total distance traveled by a vehicle is divided into line-haul distance ( $D_{LH}$ ), which represents the distance between the depot and the service area, and local distance ( $D_L$ ), which estimates the overall distance between customers in the area. Total delivery time ( $T$ ) is approximated by transforming distance into time, using information on urban and interurban speeds ( $v_A, v_B$ ) and time lost per stop ( $\tau$ ).

The objective of each carrier is to minimize its total delivery cost, which is mainly driven by a weighted sum of traveled distance ( $D_{LH} + D_L$ ) and vehicle time ( $T$ ). We use unit cost of traveled distance and vehicle time, denoted by  $c_d$  and  $c_t$ , respectively, which convert these metrics into monetary units. The corresponding objective function is defined in Equation (1).

The relevant parameters describing cost are the dimensions of the service area ( $A$ ), the number of customers ( $N$ ), the vehicle's load capacity ( $C$ ) and the distance from the depot to the geographical center of the service area, which is denoted by  $\rho$ . Let  $\delta$  be customer density ( $N/A$ ). We assume that each customer demands one unit of the total capacity, and that customers are spread homogeneously within the service area.

The optimal strategy of the company can be described by the metrics in equations (2-4) where  $\lambda = (c_d/2 + c_t/v_A - c_t/2v_B)/(c_d + c_t/v_A)$  is a parameter that helps us to simplify the final formulae. The following equations summarize the most important cost metrics of the model, in which the total cost is formulated as a weighted sum of distance and temporal costs.

$$c_d(D_L + D_{LH}) + c_t T \quad (1)$$

$$D_L = N \frac{\lambda + 3}{3(\delta\lambda)^{1/2}} \quad (2)$$

$$D_{LH} = N \left[ \frac{2\rho}{C} - \frac{(3\lambda)^{1/2}}{2\delta^{3/2}} \right] \quad (3)$$

$$T = N \left[ \frac{2\rho}{v_B C} + \frac{1}{(3\lambda\delta)^{1/2}} \left( \frac{1}{v_A} - \frac{1}{2v_B} \right) + \left( \frac{\lambda}{3\delta} \right)^{1/2} \frac{1}{v_A} + \tau \right] \quad (4)$$

The main implications derived from the formulae are that total costs are directly proportional to  $N$ , and that as customer density increases, local distance, time, and consequently, total cost decreases.

The above model was adapted to the case of equal market share companies in (4). The model allows evaluating the operating costs of a system with a UCC and comparing them with the case where no UCC exists. In a particular case study, results are promising with a 12-14% of operational cost savings. In the following section we will build the model for the general case.

## 2.2. New model for different market share companies

From here on, we assume there is a delivery zone of area  $A$ , where  $M$  companies operate and a total of  $N$  customers are located uniformly. Each of the companies gives service to  $N_i$  customers,  $i = 1, \dots, M$ , with  $N = \sum_{i=1, \dots, M} N_i$ . The customer density of each company is denoted by  $\delta_i = N_i/A$ ,  $i = 1, \dots, M$ . Note that  $\delta_i$  is smaller than the overall demand density  $\delta = N/A$ . The distance from the depot to the geographical center of the service area is denoted by  $\rho$ . We further assume a fixed capacity  $C$  for the vehicles that perform urban distribution. In the case where no UCC exists, those vehicles traveling from depot to the service area also have capacity  $C$ , whereas we consider that companies use (bigger) trucks with capacity  $B = k_C C$ , ( $k_C \geq 1$ ) when they use the consolidation center. The parameter  $k_C$  represents the relative increment of vehicle capacity in line-haul distribution and it is called *capacity enlargement*. We further assume that the UCC is located at distance  $\phi$  from the geographic center of the service region with  $\phi = k_\rho \rho$ , ( $k_\rho \leq$

1, i.e. the UCC is closer than the company's depot to the geographic center of the service region). The parameter  $k_\rho$  is called *depot distance reduction*. It relates two distances: the distance  $\rho$  from the geographical center of the service area to the depot of the carrier and the distance  $\phi$  from the geographical center of the service area to the UCC.

Next, we present a continuous model for different market share distributions, which allows a comparison of two potential urban delivery strategies: A) a system without the UCC and B) a system with the UCC. Both strategies are compared in terms of costs, distance, and time consumption; assuming that all the companies are trying to minimize their costs. As mentioned before, in the system without a UCC it is assumed that each company carries the distribution to its customers independently with its own fleet. The total costs are the sum of the costs of each individual company. On the contrary, in the UCC system it is assumed that the costs are split in two delivery phases: the costs that each company undergoes to bring the goods to the consolidation center with its own fleet and the costs of the neutral freight carrier for last mile distribution. It is further assumed that the distribution center is not a warehouse and that goods are received and shipped on the same day. Thus, no holding costs are incurred. Equations (5-7) summarize the results without a UCC, i.e., when each transport operator acts independently from the others, whereas Equations (8-10) show the results for strategy B, when operators act in collaboration through the use of a UCC. Note that we use  $D_{LHA}$ ,  $D_{LA}$  and  $T_A$ , and  $D_{LHB}$ ,  $D_{LB}$  and  $T_B$  to refer to the metrics of Strategy A and B respectively.

$$D_{LA} = \frac{\lambda + 3}{3\lambda^{1/2}} \sum_{i=1}^M \frac{N_i}{\delta_i^{1/2}} \quad (5)$$

$$D_{LHA} = N \frac{2\rho}{C} - \frac{(3\lambda)^{1/2}}{2} \sum_{i=1}^M \frac{N_i}{\delta_i^{3/2}} \quad (6)$$

$$T_A = N \left[ \frac{2\rho}{v_B C} + \tau \right] + \sum_{i=1}^M \frac{N_i}{\delta_i^{1/2}} \left( \frac{1}{(3\lambda)^{1/2}} \left( \frac{1}{v_A} - \frac{1}{2v_B} \right) + \left( \frac{\lambda}{3\delta} \right)^{1/2} \frac{1}{v_A} \right) \quad (7)$$

$$D_{LB} = \frac{\lambda + 3}{3\lambda^{1/2}} \frac{N}{\delta^{1/2}} \quad (8)$$

$$D_{LHB} = N \frac{2\rho}{C} \left( k_\rho + \frac{1}{k_C} \right) - \frac{(3\lambda)^{1/2}}{2} \frac{N}{\delta^{3/2}} \quad (9)$$

$$T_B = N \left[ \frac{2\rho}{v_B C} \left( k_\rho + \frac{1}{k_C} \right) + \tau \right] + \frac{N}{\delta^{1/2}} \left[ \frac{1}{(3\lambda)^{1/2}} \left( \frac{1}{v_A} - \frac{1}{2v_B} \right) + \left( \frac{\lambda}{3} \right)^{1/2} \frac{1}{v_A} \right] \quad (10)$$

The new critical aspects to decide on whether the consolidation center is beneficial in terms of distribution costs are the number of collaborating companies and the market structure. Capacity enlargement and depot distance reduction are also crucial to the study of the viability of the consolidation strategy. These will be discussed in the results section.

### 2.3. Analysis for several market share distributions

Some data of transport companies registered in Barcelona (Spain) was analyzed to check the heterogeneity of real markets. In particular, the number of transport companies classified by sales revenue and the number of employees, which are two variables closely related to market share. We could observe that the more significant group was of small companies, i.e., the smallest group both in sales and employees. But then, other groups were also present, with some sparsity.

The difficulty to obtain reliable data of market share in a particular area leads us to analyze different possible distributions. In the following section, we formulate some possible market distribution based on some analytically

simple functions to present a preview study. Since we cannot guarantee that in reality the market adjusts to some known functions, in the subsequent section a full set of potential market distributions will be proposed.

*Non-equal market share structures.* We analyze four families of market share distributions based on the most analytically simple functions. We assume that the total demand ( $N$ ) has to be distributed differently among  $M$  companies. For each family, we further assume an extra condition to analyze one representative of the family in particular.

- i. Grouped. There are two types of companies, one that has many customers and the other which has much less. We can describe this distribution with Equation (11), where the parameters ( $a, b$ ) have to be determined. For instance, in this case, we assume that big companies have twice as many customers as smaller companies ( $2a = b$ ).

$$\begin{cases} N_i = a = 2N/3M, & i = 1, \dots, M/2 \\ N_i = b = 4N/3M, & i = M/2 + 1, \dots, M \end{cases} \quad (11)$$

- ii. Lineal. Each company has a different number of customers and the distribution among them follows a lineal increase. Equation (12) describes the distribution where parameters ( $a, b$ ) must be fixed. For instance, assuming that if there was another company smaller than the smallest of this distribution, its demand would be zero (i.e., imposing  $a = 0$ ).

$$N_i = a + bi = (2N/M(M + 1))i, \quad i = 1, \dots, M \quad (12)$$

- iii. Exponential. Each company has a different number of customers and the distribution among them follows an exponential increase. There could be bigger companies and smaller companies than in the lineal case. The number of customers per company is more varied. Equation (13) represents the distribution, and we force  $b = 3/M$  to bend the distribution and distinguish it from the lineal one. Then  $a = (N/M)/\sum_{i=1}^M \exp(3i/M)$ .

$$N_i = a \exp(bi) = \frac{(N/M)}{\sum_{i=1}^M \exp(3i/M)} \exp(3i/M), \quad i = 1, \dots, M \quad (13)$$

- iv. Uniform. All companies have the same number of customers. This is the equal market share assumption developed in Roca-Riu et al. (2012) that can be treated as a particular case. See Equation (14). It is easy to check that the formulae presented in the previously mentioned work, coincide with the ones presented here under uniform demand.

$$N_i = a = N/M, \quad i = 1, \dots, M. \quad (14)$$

*Full set of potential market distributions.* In a general case, the structure of the market is unknown. The structures presented previously can seem rather limited, so we propose an extended set of distributions. This set can cover any possible distribution of customers among carriers.

We must distribute  $N$  customers among  $M$  companies in any possible way. Using combinatorics, we can think of this as an assignment of an integer number from  $1 \dots N$  to  $M$  carriers with some restrictions. Note that not all combinations represent meaningful distributions of customers. In particular, we should take into account the following:

- Exact coverage of the total demand. That is, each customer is assigned to one company.
- No combination of customers is repeated. The order in which the number of customers is assigned to a company is not important since the resulting distribution is the same.
- Assignment of at least one customer per company. Each company should have at least one customer, otherwise this assignment would not have  $M$  companies.

To obtain all the possible distributions of customers among carriers, we have designed an iterative algorithm that enumerates and generates all possible distributions. Each possible distribution will be uniquely represented by a code defined by  $M$  integer numbers of customers sorted increasingly. For instance, if in one distribution the companies have 5,7,3,1,6 customers each, the unique code is: {1,3,5,6,7}. Thus, companies are implicitly ordered by increasing number of customers, so that the "first" company has the smallest number of customers and the "last" company has the largest number of customers. The algorithm builds the distributions following this unique code criterion.

The algorithm defines  $H_i$ , as the set of all possible combinations of numbers of customers among the first  $i$  companies, when  $N$  customers are distributed among  $M$  companies.  $H_1$  is easy to generate. Then, for  $i = 2, \dots, M - 1$ ,  $H_i$  is iteratively built from  $H_{i-1}$ . Finally,  $H_M$  is obtained by completing each distribution in  $H_{M-1}$  with the remaining uncovered demand. See Algorithm 1 for details.

Algorithm 1:

Step 1

$$H_1 := \{\{1\}, \{2\}, \{3\}, \dots, \{N/M\}\}.$$

Note that if we assign more than  $\lfloor N/M \rfloor$  to the first company, we have to assign at least the same value to all the companies to keep the increasing order of the code. That would represent exceeding the total demand. Note that  $\lfloor x \rfloor$  means the maximum integer number no greater than  $x$ .

Step 2

For  $i = 1, \dots, M - 2$  do

For each  $\bar{h} \in H_i$ , generate new possible distributions of  $H_{i+1}$  based on  $\bar{h}$  (i.e. with the first  $i$  elements equal to  $\bar{h}$ )

If  $\bar{h} = \{h_1, h_2, h_3, \dots, h_i\}$ , with  $h_1 \leq h_2 \leq h_3 \leq \dots \leq h_i$  define all the possible  $r$  distributions of  $H_{i+1}$ .

$$\bar{h}_1 = \{h_1, h_2, h_3, \dots, h_i, h_i\},$$

$$\bar{h}_2 = \{h_1, h_2, h_3, \dots, h_i, h_i + 1\},$$

$$\bar{h}_3 = \{h_1, h_2, h_3, \dots, h_i, h_i + 2\},$$

...

$$\bar{h}_r = \left\{ h_1, h_2, h_3, \dots, h_i, \left\lfloor \frac{N - (\sum_{j=1..i} k_j)}{M-i} \right\rfloor \right\}.$$

Similarly to the previous comment of Step 1, we cannot assign more than the demand not yet assigned divided by the number of the remaining companies. We need to keep the increasing order.

$$H_{i+1} := \{\{\bar{h}_1\}, \{\bar{h}_2\}, \dots, \{\bar{h}_r\}\}$$

End do

Step 3

For each  $\bar{h} \in H_{M-1}$ ,  $\bar{h} = \{h_1, h_2, h_3, \dots, h_{M-1}\}$  generate the final distribution.

$$\hat{h} = \{h_1, h_2, h_3, \dots, h_{M-1}, N - \sum_{j=1..i} h_j\}$$

#### 2.4. Trade-off between minimum carrier dimension and savings

Medium-size and large carriers could oppose to including small carriers in the UCC, as mentioned before. The reason for this is that small carriers do not significantly increase the number of customers, but are greatly benefitted from consolidation centers. With the formulae built in this section, we can decide the threshold for the minimum demand of a company to join the consolidation center, depending on its savings contribution.

Let  $N_T, \delta_T$  refer to the number of customers and density demand of the collaborating companies, respectively; and  $N_S, \delta_S$ , the corresponding values for the individual company that wants to join the collaborative system. Using the same methodology of the previous section we can derive the formulae for this case. We will compute the costs of the two situations: C) the current situation where the individual company distributes independently, see Equations (15-17), and D) a hypothetic situation where the individual company joins the collaborative system, see Equations (18-

20). Thus, we can establish a trade-off between the dimension of the individual carrier, and the savings of the hypothetic collaboration system. Note that we use subscript  $C$  to refer to the metrics of state  $C$ , and subscript  $D$ , respectively, for state  $D$ . Recall that  $A$  and  $B$  refer to strategies of the previous section.

$$D_{LC} = \left[ N_T \frac{\lambda + 3}{3(\lambda\delta_T)^{1/2}} \right] + \left[ N_S \frac{\lambda + 3}{3(\lambda\delta_S)^{1/2}} \right] \quad (15)$$

$$D_{LHC} = \left[ N_T \frac{2\rho}{C} \left( k_\rho + \frac{1}{k_C} \right) - \frac{(3\lambda)^{1/2}}{2} \frac{N}{\delta_T^{3/2}} \right] + \left[ N_S \frac{2\rho}{C} - \frac{(3\lambda)^{1/2}}{2} \frac{N}{\delta_S^{3/2}} \right] \quad (16)$$

$$T_C = \left[ N_T \left( \frac{2\rho}{v_B C} \left( k_\rho + \frac{1}{k_C} \right) + \frac{1}{(3\lambda\delta_T)^{1/2}} \left( \frac{1}{v_A} - \frac{1}{2v_B} \right) + \left( \frac{\lambda}{3\delta_T} \right)^{1/2} \frac{1}{v_A} + \tau \right) \right] \\ + \left[ N_S \left( \frac{2\rho}{v_B C} + \left( \frac{1}{(3\lambda\delta_S)^{1/2}} \left( \frac{1}{v_A} - \frac{1}{2v_B} \right) + \left( \frac{\lambda}{3\delta_S} \right)^{1/2} \frac{1}{v_A} \right) + \tau \right) \right] \quad (17)$$

$$D_{LD} = (N_T + N_S) \frac{\lambda + 3}{3(\lambda(\delta_T + \delta_S))^{1/2}} \quad (18)$$

$$D_{LHD} = (N_T + N_S) \frac{2\rho}{C} \left( k_\rho + \frac{1}{k_C} \right) - \frac{(3\lambda)^{1/2}}{2} \frac{N}{(\delta_T + \delta_S)^{3/2}} \quad (19)$$

$$T_D = (N_T + N_S) \left[ \frac{2\rho}{v_B C} \left( k_\rho + \frac{1}{k_C} \right) + \tau \right] + \frac{(N_T + N_S)}{(\delta_T + \delta_S)^{1/2}} \left[ \frac{1}{(3\lambda)^{1/2}} \left( \frac{1}{v_A} - \frac{1}{2v_B} \right) + \left( \frac{\lambda}{3} \right)^{1/2} \frac{1}{v_A} \right] \quad (20)$$

### 3. Results and Conclusion

In this section we will present several results of the previous formulations for the various sets of parameter values based on European cities (see Table 1). The parameters that refer to the area ( $A$ ) and distance to the nearest depot ( $\rho$ ) have been evaluated within an interval of possible alternative situations. Speeds are approximate realistic values for urban trips based on INE (2003) database. Capacity of vehicles and time lost per stop are taken from (UITP, 2009; Prointec, 1997). Unit cost parameters are taken from (PTOP 2008; CCBCN, 2008). The study of the parameters  $k_C$  and  $k_\rho$  is detailed in Roca-Riu et al. (2012). These are average values and are suitable as design parameters for the operative UCC.

Table 1. Summary of the most important parameters regarding European cities

Parameters	Values	Units	Parameters	Values	Units
$A$	[1,20]	[km <sup>2</sup> ]	$C$	[5,15]	[stops]
$\delta$	[2,100]	[stores/km <sup>2</sup> ]	$c_d$	0.3	[€/km]
$\rho$	[5,50]	[km]	$c_t$	26.36	[€/h]
$v_A$	25	[km/h]	$k_C$	1.4	[-]
$v_B$	50	[km/h]	$k_\rho$	0.1	[-]
$\tau$	0.3	[h]	$M$	10	[-]

First, we will present the results of the trade-off between minimum carrier dimension and savings of the last subsection of Methodology Section. The reason is that we will further use these results in the application of the full set of potential market structures. Secondly, we will analyze the results for several market share distributions. Finally, a sensitivity analysis of the parameters will be presented.



### 3.1. Trade-off between minimum carrier dimension and savings

The analysis of this relation will be done through the analysis of one parameter that relates  $N_T$  to  $N_S$  (number of customers of the consolidation center and number of customers of the carrier that wants to join the UCC, respectively). We use the expression  $N_S = k_N N_T$  with  $k_N \in [\varepsilon, 0.5]$ , where  $\varepsilon > 0$ , i.e. the new carrier has a number of customers that is a portion of the customers that receive goods from the UCC. The model in the previous section provides a useful tool that companies can use to limit the participation of very small carriers. For a new carrier to be admitted to join the system, the consolidation center may require that its incorporation will imply a minimum percentage reduction on the unit cost per customer. In Fig. 1a, we present the unit cost of distribution per customer as a function of  $k_N$  for: i) the independent carrier, ii) the current UCC system, iii) the case where the independent carrier joins the UCC. In Fig. 1b, we present the savings between the current costs of the UCC and the UCC plus the new carrier. We compare the unit cost per customer in both scenarios using the difference of these values expressed in percentage.

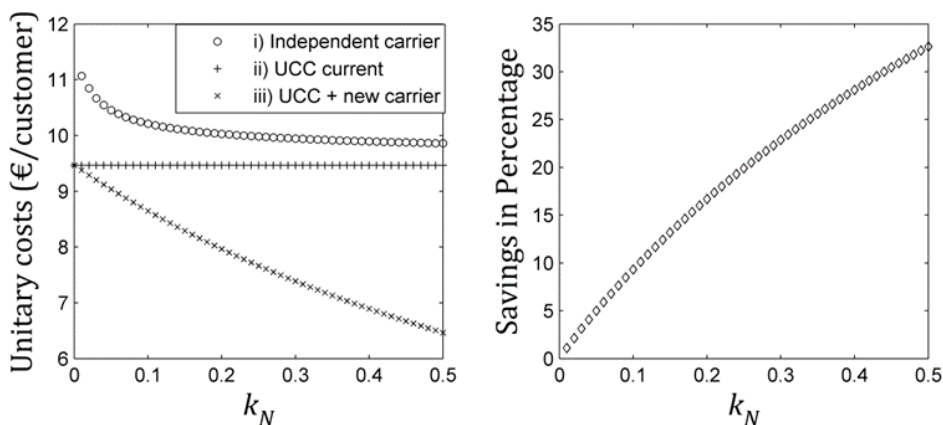


Fig. 1. Cost and savings for inclusion of one carrier to the UCC. (a). Unit costs as a function of  $k_N$ .(b). Percentage savings of the future system.

In Fig. 1a, we can observe the decrease in unit costs as the number of customers of the independent carrier increases ( $k_N$ ). Something similar happens as the new carrier increases the overall UCC demand, by incorporating its customers. Costs of the current UCC system remain fixed as they are not affected by the demand of the independent carrier. Fig. 1b shows the increase in savings of unit costs as the demand that the new independent carrier brings to the system increases. Potential savings range from 5% if the independent carrier has 5% of the customers of the consolidation center up to a 32.5% if the independent carrier brings 50% of the demand of the UCC

### 3.2. Results for several market share distributions

We analyze how the number of companies participating affects the costs for the different market share distributions proposed in the previous section, regarding the four families based on simple analytical functions. In Fig. 2a, we present the total costs for each of the considered market share structures (grouped, linear, exponential, and uniform) as well as the total distribution costs for the same overall demand by the use of a UCC. We can see that total costs are similar in the four market share distributions and that UCC costs are slightly lower. As could be expected, the difference in cost grows as more companies are considered. In Fig. 2b, we present the percentage savings of UCC costs with respect to the costs of each market share structure. We observe that the uniform distribution is the one that provides more savings; however, other distributions present the same range of savings, with a maximum difference that is smaller than 0.5%.

From the above figures, it is evident that the more companies collaborate, the more demand is consolidated, and thus, there are more savings. We can conclude that different market structures do not affect the operational savings of an urban consolidation center significantly. However, to extensively check this conclusion, we will present the results with the full set of potential market distributions proposed in the previous section.

The size of the full set of potential market distributions for  $N$  customers among  $M$  companies grows quickly with  $N$ . Thus, it is not possible to analyze the complete set, even when  $N$  and  $M$  take small values. In order to reduce the number of distributions to analyze, we have limited the participation of companies with a small number of costumers, as they would not be accepted by medium-large carriers. Using the analysis of the results of the previous section, we can determine the minimum demand per company to obtain a given percentage of savings. We set the threshold to a 5% of cost reduction, which limits the minimum demand per company to 5% of the total demand of the service area.

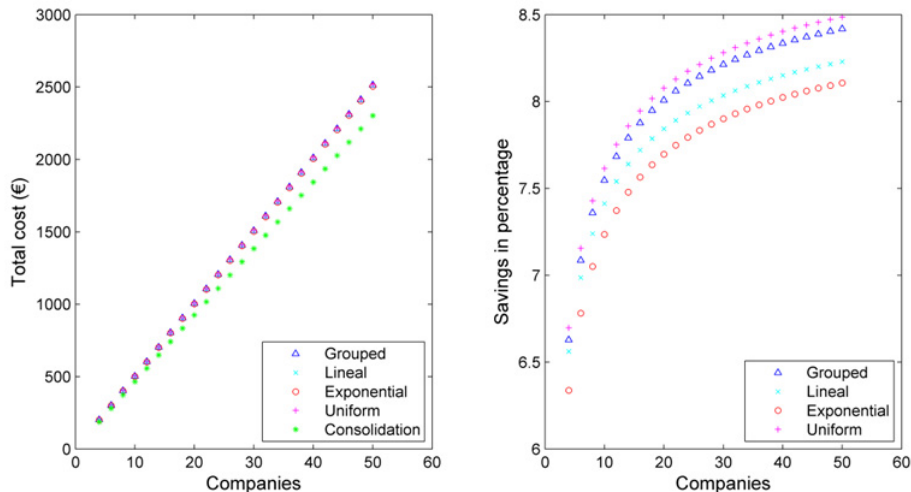


Fig. 2. Cost and savings for several market share structures. (a) Total cost for each market structure and (b) Savings in percentage depending on the market structure and the number of companies.

We generate all market distributions with the Algorithm 1 for a total of 80 customers distributed among 10 companies. The minimum demand per company is 4 customers, resulting in a total of 16,928 possible market distributions. For each generated distribution we compute the savings between the current situation with no collaboration and a total collaborative situation.

In Fig. 3, we present a histogram of savings for the full set of potential market distributions. The range of savings is between 6.3% and 7%, which states the difference between the distribution with lowest savings and the distribution with the highest savings. The differences in savings between the full set of potential market distributions are not significant, the mean is 6.79 and the variance is 0.0067. Therefore, we can conclude that market structure does not affect savings in UCC strategy.

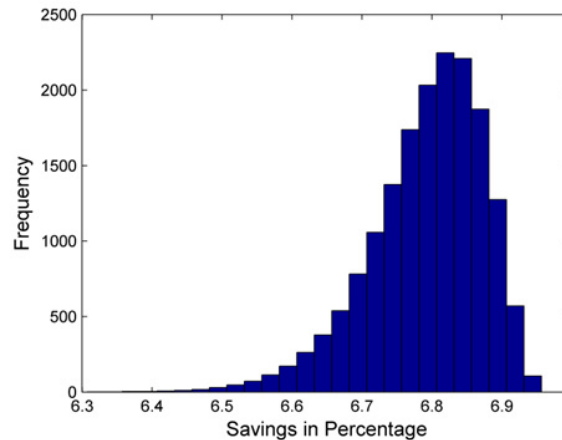


Fig. 3. Savings expressed in percentage of the full set of potential market distributions for 80 customers distributed among 10 companies.

### 3.3. Sensitivity analysis of the key parameters

This section aims to provide the range of values that guarantee savings in operation costs. The parameters defining the system are crucial to assure savings when the consolidation centers used are  $k_C$  and  $k_\rho$ . Context parameters like  $A$  or  $\delta$  are also considered, since they are chosen at planning level and they have a great influence on the behavior of the resulting system. On the contrary, parameters like  $C$ ,  $\rho$ ,  $c_d$ ,  $c_t$ ,  $v_A$ ,  $v_B$ , and  $\tau$  are less dependent on planning decisions and tend to be linked to the characteristics of each commodity, city, or region.

As we have shown that market share distribution does not significantly affect savings, in this section we will work with the equal market share distribution formulation.

The predominant term of total cost is line-haul cost, which can be significantly reduced by an appropriate combination of  $k_\rho$  and  $k_C$ . In Fig. 4, line-haul distance savings expressed in percentage are related to  $k_\rho$  and  $k_C$ . For instance, the use of a UCC with a depot distance reduction of 0.2 and a capacity enlargement of 2 yields a line-length saving of approximately 20%. The difference between savings (positive savings expressed in percentage) and losses (negative savings expressed in percentage) can be clearly observed in the intersection of the surface with the plane  $z = 0$ . That is exactly the hyperbolic curve determined by  $(k_\rho + 1/k_C) = 1$ . Moreover, for smaller values of  $k_\rho$  and larger values of  $k_C$ , more savings can be obtained.

As an example, in Fig. 5, we present the unit cost for each of the two strategies with  $k_\rho = 0.1$ ,  $k_C = 1.4$ . Note that in this case, such cost can be quite large since the data used is aggregated. The costs of the current system appear above and the values for the system with the consolidation center are below. We can observe savings around 12-14%. In general, operational cost savings in these ranges can be guaranteed.

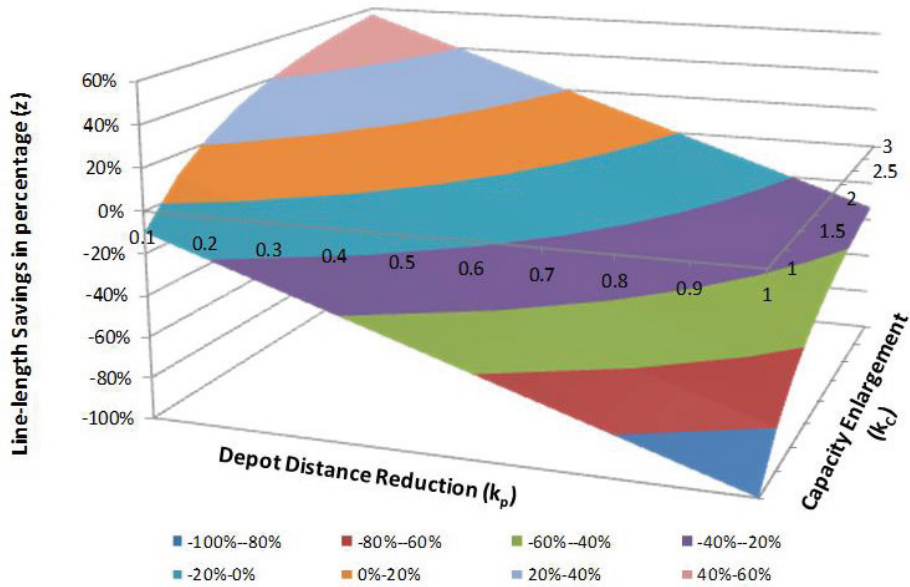


Fig. 4. Line-haul distance savings expressed in percentage depending on the value of the parameters  $k_p, k_c$  (depot distance reduction, capacity enlargement).

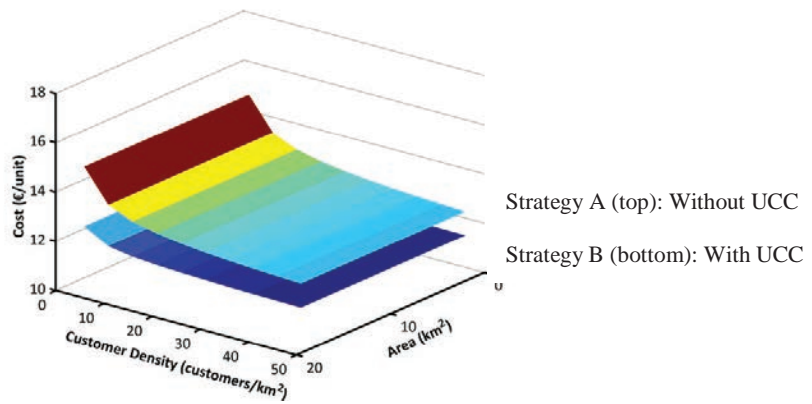


Fig. 5. Unit cost of distribution depending on the area size and customer density.

### 3.4. Conclusion

In this paper we have proposed a continuous model that analyzes an improvement in efficiency of urban distribution with the use of consolidation centers. The proposed methodology can be easily applied to a wide collection of service areas to obtain accurate approximations of the savings. The results obtained with data, based on densely populated

urban areas such as European cities, show that benefits can reach up to a 12-14% in cost savings. In addition, the model allows a sensitivity analysis of all the metrics directly involved in detail, specifically: cost, distance, and time.

We have provided a tool to determine the minimum number of customers from all the companies participating in the consolidation center needed to reach target percentage savings. This can be very useful for planning purposes, when defining the companies that can participate in the consolidation center.

We have assumed that companies with different market shares within the service area act collaboratively through a UCC. However, the different market assumption does not greatly impact savings in percentage of the resulting center, when compared to a uniform market share distribution situation. Thus, we can conclude that the distribution of customers among the companies does not significantly affect the savings of the consolidation center.

Future research on this topic could be addressed by adding constraints to make the model even more realistic, such as the time windows imposed by customers or the possibility of temporary storage in the consolidation center. Otherwise, the work could be focused on additional aspects of the system. For instance, the approximation of the costs incurred in urban consolidation centers and its financial possibilities. Or in a more general way, the distribution of the new costs and the benefits of a UCC system among all stakeholders involved.

## Acknowledgements

This research has been partially supported by the Spanish Ministry of Science and Education through projects TRA2009-14759-C02-01 and MTM2009-14039-C06-05, and ERDF funds. Their support is gratefully acknowledged.

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