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An evaluation of urban consolidation centers through logistics systems analysis in circumstances where companies have equal market shares

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Abstract

Urban goods distribution is crucial for the economic vitality of cities but at the same time it causes several problems with regard to traffic congestion and environment. This paper proposes a strategic solution combining cooperation between freight carriers through the use of a consolidation terminal to reduce operational costs, and consequently the negative impacts on the city. The current system without consolidation center is compared in terms of operational costs with a future system where a consolidation center is implemented. Continuous analysis is used to formulate a basic model to estimate costs and benefits. Finally, general results are discussed and a case study in L'Hospitalet de Llobregat (Metropolitan Area of Barcelona) is analyzed. Results are promising with a 12-14% of operational cost savings in a general case. From the case study we conclude that the commitment of the 40% of demand allows covering the costs of terminal implantation.

Keywords: Urban consolidation center; mathematical formulation

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1. Introduction

Urban distribution of goods currently entails several problems to the stakeholders of the urban system. Carriers spend most part of the time and expend a significant portion of the cost in the last-mile distribution due to increasing levels of traffic congestion, lack of unloading/loading zones, and other

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inefficiencies. Although urban distance represents a small part of the total traveled distance, it represents a 28% of the total costs. In turn, urban citizens often undergo environmental effects like pollution, noise, or space competition; and customers are more demanding in terms of time windows, frequencies, and competitive prices.

The problem of establishing effective operative measures to improve urban distribution is challenging because the market is heterogeneous with multiple types of products, roles, and conflicting objectives. Although it causes great inconveniences in most of the cities there is a lack of guidelines or leadership from the administration to regulate and organize the distribution in order to make it more efficient. Thus, there is a special need for innovative solutions involving public and private parts to produce attractive benefits for both companies and urban citizens.

We propose a strategic solution that combines cooperation between freight carriers through the use of a public freight terminal. Transport operators can bring the load to the Consolidation Center (CC) with bigger vehicles and less time restrictions. Then, a neutral freight carrier does the local delivery with higher costumer density. We use a continuous approximation model to compare the usual systems with the system with a CC. Essential parameters are analyzed and a case study is presented.

Proposals of the same nature as the one we present are detailed in (Köhler, 2001) where actual solutions were implemented in German cities. However, results obtained come from real experiences and depend on each case study, so no general tendencies or general facts can be concluded from that work. We use the methodology of Logistic System Analysis (Daganzo, 2005) to define an accurate model for predicting benefits of the CC proposed. Continuous approximation models with robust solutions provide tendencies in the sensitive analysis and give us more insights about the solutions in order to gain knowledge for general cases; this is what differentiates us from previous works. Another paper which follows a similar approach is Kawamura (2007), but our modeling hypotheses are substantially different to guarantee benefits for the CC. For instance, they consider holding costs, adjust the frequency of the dispatch and consider big trucks entering the city without problems. Regarding cities data, our approach is more focused in dense urban contexts: higher costumer density, smaller areas and consequently shorter distances between depots and destinations.

The reminder of this paper is organized as follows: Section 2 states the objectives of the study and describes the problem. In Section 3 the models are formulated, analytically solved, and theoretically discussed. Section 4 presents the general case study with recommended ranges of parameters and the case study for L'Hospitalet the Llobregat, a city in the metropolitan area of Barcelona. Finally, conclusions are drawn in Section 5.

2. Objectives, problem description and assumptions

The purpose of this paper is to quantify the effects of the implantation of a Consolidation Center (CC) to regulate urban distribution in an area of the city and to study under which circumstances it is globally beneficial for all the participants involved. To do so, we aim to provide an accurate methodology which determines faithful approximation of all the costs involved.

The main idea behind our approach is that during determined time periods (preferably at night), carriers from every company will bring the goods to the center with the possibility of using larger vehicles. During the day, with higher costumer density, local deliveries will be performed more efficiently by a neutral freight carrier.

To easily describe the service area, we assume that several parameters of the zone are homogeneous, such as zone dimension, demand density, truck capacities, distance to nearer depots, unit costs, number of carriers, and location of the center, among others. We further assume that the center will not be a warehouse, so goods will be received and shipped every day. We also assume similar market-share carriers are able to collaborate and build an urban CC with some public subsidies.

Key definition variables are the dimensions of the vehicle zone delivery partition, which is assumed to be rectangular, vehicle load and the trips per time horizon of each vehicle. The resulting cost decision function, traveled distance and vehicles-hour, can be simply formulated from the above variables and the parameters. Then, the model will be able to predict costs related to time and distance and any other interesting system metric.

3. Model and results

A basic model is formulated to find the optimal strategy that one company should use to serve its clients spread over a delimited area from a depot. Then the model is adapted to formulate and compare two alternative scenarios: A) Without CC or B) With CC.

3.1. General model description

Let us assume that one company has to serve N customers in a rectangular zone of area A from a depot located at distance ρ from the center of the service area, with vehicles of capacity C. Let δ be customer's density. The company designs the tours with the objective of minimizing a weighted sum of distance costs (minimum tours) and temporal costs (minimum time consumption).

As typical routing strategies do, first the region is partitioned in groups of approximately S points each. Note that S will be limited by time and capacity constraints. Then vehicle tours within the time horizon are designed. Vehicles travel from the depot to some point in its zone, serve the clients and return to the depot. We will call *line-haul distance* to the distance from the depot to the nearest point in its zone plus the distance from the last visiting point to the depot. And *local distance* is the distance covered during the delivery of the items. Let m be the average number of vehicle's trips. Given the density of streets in urban areas we use the square grid metric to determine distances in the service area. Thus, S points should be located in a connected area. We assume that zones are rectangles with sides $2w$ and P, which form a partition of the whole delivery region.

We following compute the total distance traveled to give service to a costumer by dividing the distance in local and line-haul components. The local distance traveled is independent of the point where the route starts or ends the delivery. Newell et. al (1986) proposed a simple (non-optimal) strategy for visiting the points in each zone and showed that if we use nearly rectangular partitions of the region, they should be elongated toward the depot. If vehicles carry a full load, the number of points in the rectangle should be C, that using density, should be equivalent to $2wP\delta$. However, we might be interested in reducing the average number of points to S. So we will denote the number of expected customers inside a rectangle as S and use the following equality $2wP\delta = S$ to reduce one variable. To estimate the local length of a tour as a function of w and S, we extend Daganzo's proposal and divide the rectangle into two bands each of width w. Then, each route visits points in non decreasing coordinate x along the length of the rectangle on the way out and decreasing x on the way back (See Fig. 1). If points are randomly distributed in space, one can evaluate the expected total distance. We divide the distance into traverse and longitudinal, yet we use square grid metric to approximate the distance. The average traverse travel distance per point is simply the average distance between two random points on an interval of width w, that is $w/3$. The total longitudinal travel in the rectangle is $2P$ or $2P/S$ per point and using the mentioned equality ($2wP\delta = S$), we obtain $1/\delta w$. The average line-haul distance for a vehicle will be $2\rho - P$ or $(2\rho - P)/S$ per point. We subtract P to the distance of the depot due to the relative position of the service areas with the depot and again replacing P using the equality we obtain $(2\rho - S/2\delta w)/S$. Finally, adding line-haul and local distance we obtain an approximation of the total distance traveled per point:

$$d = \frac{w}{3} + \frac{1}{\delta w} + \frac{2\rho - \frac{S}{2\delta} w}{S}$$

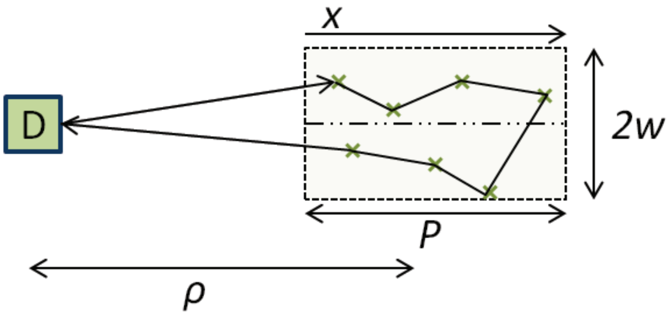

Fig. 1. Local strategy to cover all points

Apart from costs derived from the covering of distance, costs also come from the time spent during the delivery. Using v_A, v_B and τ as urban speed inside the service area, interurban speed from the depot to the service area, and time lost per customer's unloading/loading of a vehicle respectively, the total time per vehicle trip is:

$$\frac{2\rho - P}{v_B} + \frac{2P}{v_A} + \frac{wS}{3v_A} + \tau S$$

Then, the time devoted to each customer can be obtained from the above equation divided by the customers served with one vehicle (S).

$$\frac{2\rho}{v_B S} - \frac{1}{2w\delta v_B} + \frac{1}{w\delta v_A} + \frac{w}{3v_A} + \tau$$

The objective function is built by a weighted sum of distance costs and time related costs, with unit cost parameters c_d and c_t:

$$min_{w,S,m} N\left[\left(c_d + \frac{c_t}{v_B}\right)\frac{2\rho}{S} + \left(\frac{c_d}{2} + \frac{c_t}{v_A} - \frac{c_t}{2v_B}\right)\frac{1}{w\delta} + \left(c_d + \frac{c_t}{v_A}\right)\frac{w}{3} + c_t\tau\right] \quad (1)$$

$$S \le C \quad (2)$$

$$\frac{2\rho}{v_B} - \frac{S}{2w\delta v_B} + \frac{S}{w\delta v_A} + \frac{wS}{3v_A} + \tau S \le \frac{Y}{m} \qquad (3)$$

$$w, S, m \ge 0 \text{ Continuous} \qquad (4)$$

Constraints (2) and (3) model the limitations on the capacity of the vehicles C or on the time horizon Y.

We can solve the problem formed by equations (1)-(4) analytically due to the nature of its variables. As m can become as small as desired, constraint (3) can be omitted making m equal to $Y / ((2\rho/v_B - S/(2w\delta v_B) + S/$ 〖$w\delta v_A$〗 $+ wS/(3v_A) + \tau S))$ which is, obviously, positive. Then, in order to minimize the objective function, S should be as big as possible, which makes S equal to C, and from minimum conditions we obtain $w^* = \sqrt{}(3(c_d/2 + c_t/v_A - c_t/(2v_B))/\delta(c_d + c_t/v_A))$. Let us call $\lambda = ((c_d/2 + c_t/v_A - c_t/(2v_B)))/((c_d + c_t/v_A))$, and so $w^* = \sqrt{}(3\lambda/\delta)$. Finally, the most important metrics are summarized in the Table 1.

Table 1. Summary of the most important metrics of the general model

Local distance	$D_L = N\frac{\lambda + 3}{3(\delta\lambda)^{1/2}}$
Line-haul distance	$D_{LH} = N\left[\frac{2\rho}{C} - \frac{(3\lambda)^{1/2}}{2\delta^{3/2}}\right]$
Time	$T = N\left[\frac{2\rho}{v_B C} + \frac{1}{(3\lambda\delta)^{1/2}}\left(\frac{1}{v_A} - \frac{1}{2v_B}\right) + \left(\frac{\lambda}{3\delta}\right)^{1/2}\frac{1}{v_A} + \tau\right]$
Cost	$c_d(D_L + D_{LH}) + c_t T$

The costs of the system are proportional to N, the total number of customer of the system. The square root of customer density is dividing the terms in the total cost expression regarding local distribution, whereas capacity is dividing the terms regarding line-haul distribution. Finally, there is a constant time cost of stopping.

3.2. Model for consolidation and non-consolidation strategies

We assume that M>1 equal-market share companies give service to the N costumers, with $\widehat{N} = N/M$ customers each, therefore, $\hat{\delta} = \delta/M$ which is smaller than δ. In the collaborating strategy, we consider that companies can use bigger trucks with capacity $B = k_C C$ ($k_C \ge 1$), and that the CC is located at distance ϕ from the center of the service region ($\phi = k_\rho \rho$ with $k_\rho \le 1$). Note that k_C represents the enlargement of vehicle capacity in the line-haul distribution. We will call *capacity enlargement* to this parameter. Similarly, k_ρ represents the reduction of the distance from the closest depot to the final destinations. We will call depot *distance reduction* to this parameter. The two strategies that we describe next will be compared in terms of costs, distance, and time consume, assuming that all the companies try to minimize their costs. To this end, we compute the total cost of all the companies: In strategy A acting independently of other transport operators, i.e., without CC (See Table 2); in strategy B acting in collaboration through the use of a CC (See Table 3).

Table 2. Summary of the most important metrics of the model without consolidation

Local distance	$D_{LA} = M\widehat{N}\frac{\lambda+3}{3(\hat{\delta}\lambda)^{1/2}} = N\frac{\lambda+3}{3\left({}^{\delta}/_{M}\,\lambda\right)^{1/2}} = M^{1/2}N\frac{\lambda+3}{3(\delta\lambda)^{1/2}}$
Line-haul distance	$D_{LHA} = M\widehat{N}\left[\frac{2\rho}{C} - \frac{(3\lambda)^{1/2}}{2\hat{\delta}^{3/2}}\right] = N\frac{2\rho}{C} - M^{3/2}N\frac{(3\lambda)^{1/2}}{2\delta^{3/2}}$
Time	$T_A = M\widehat{N}\left[\frac{2\rho}{v_B C} + \frac{1}{(3\lambda\hat{\delta})^{1/2}}\left(\frac{1}{v_A} - \frac{1}{2v_B}\right) + \left(\frac{\lambda}{3\hat{\delta}}\right)^{1/2}\frac{1}{v_A} + \tau\right] =$ $N\left[\frac{2\rho}{v_B C} + M^{1/2}\left(\frac{1}{(3\lambda\delta)^{1/2}}\left(\frac{1}{v_A} - \frac{1}{2v_B}\right) + \left(\frac{\lambda}{3\delta}\right)^{1/2}\frac{1}{v_A}\right) + \tau\right]$
Cost	$c_d(D_{LA} + D_{LHA}) + c_t T_A$

Table 3. Summary of the most important metrics of the model with consolidation

Local distance	$D_{LB} = N\frac{\lambda+3}{3(\delta\lambda)^{1/2}}$
Line-haul distance	$D_{LHB} = M\widehat{N}\frac{2\rho}{B} + N\left[\frac{2\phi}{C} - \frac{(3\lambda)^{1/2}}{2\delta^{3/2}}\right] =$ $N\frac{2\rho}{k_C C} + N\frac{2k_\rho \rho}{C} - N\frac{(3\lambda)^{1/2}}{2\delta^{3/2}} =$ $N\frac{2\rho}{C}\left(k_\rho + \frac{1}{k_C}\right) - N\frac{(3\lambda)^{1/2}}{2\delta^{3/2}}$
Time	$T_B = N\left[\frac{2\rho}{v_B B} + \frac{2\phi}{v_B C} + \frac{1}{(3\lambda\delta)^{1/2}}\left(\frac{1}{v_A} - \frac{1}{2v_B}\right) + \left(\frac{\lambda}{3\delta}\right)^{1/2}\frac{1}{v_A} + \tau\right] =$ $N\left[\frac{2\rho}{v_B C}\left(k_\rho + \frac{1}{k_C}\right) + \frac{1}{(3\lambda\delta)^{1/2}}\left(\frac{1}{v_A} - \frac{1}{2v_B}\right) + \left(\frac{\lambda}{3\delta}\right)^{1/2}\frac{1}{v_A} + \tau\right]$
Cost	$c_d(D_{LB} + D_{LHB}) + c_t T_B$

The critical parameters to decide if the consolidation is benefitting in terms of distribution costs are: the number of companies collaborating, the capacity enlargement and the depot distance. It is clear that total local distance is reduced by the proportion of the square root of the companies participating. The line-haul distance has two main components. The first component can be compared with different values of k_C and k_ρ. If $\left(k_\rho + 1/k_C\right) = 1$ the first line-haul distance component is kept. If the value is less than one, more savings can be obtained proportionally to this value. The second component is negligible as it is one order of magnitude less than the first. Distribution time has a more complex formulation than distance; in fact, time is a reformulation of distance with speed parameters. In any case, more part of the distance is covered with interurban speed, so time is also reduced.

3.3. Sensitivity analysis

Some of the parameters will be analyzed in an isolation manner, meaning that all other parameters will be fixed. The results provide insight in the performance of the metrics. In Fig. 2, the effect of the number of companies is related to the savings in percentage of local distance. The quadratic root relationship can be clearly observed. The savings in percentage in local distance are important with the first committing companies, then the increments are limited.

In Fig. 3, line-haul distance savings in percentage are related to (k_ρ, k_C). For instance, with the use of a CC that provides a depot distance reduction of 0.2 and a capacity enlargement of 2 percentual line-length saving are around 20%. The difference between savings (positive percentual savings) and losses (negative savings in percentage) can be clearly observed in the intersection of the surface with the plane $\big(k_\rho +$ *1kC=1* . Moreover, the linear effect of *kρ* (if the surface is projected in the y plane) and the inverse effect of k_C (if the surface is projected in the x plane) are reflected in Fig. 3.

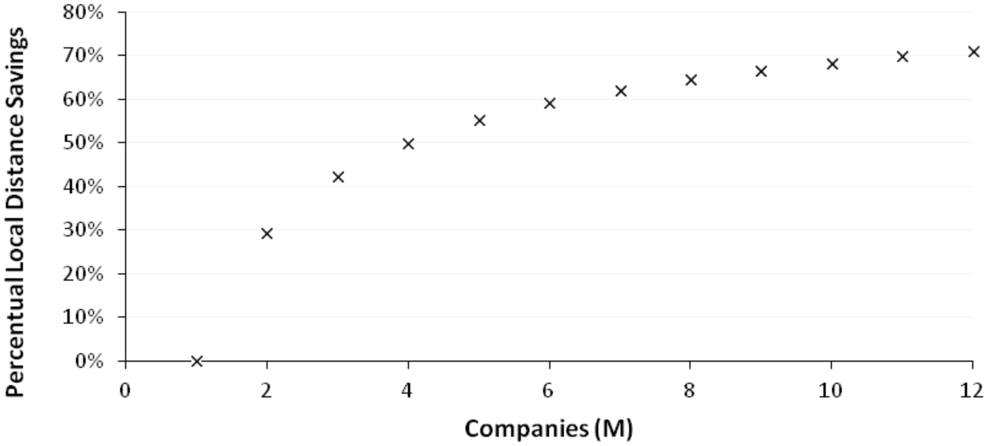

Fig. 2. Local distance savings in percentage depending on the number of companies

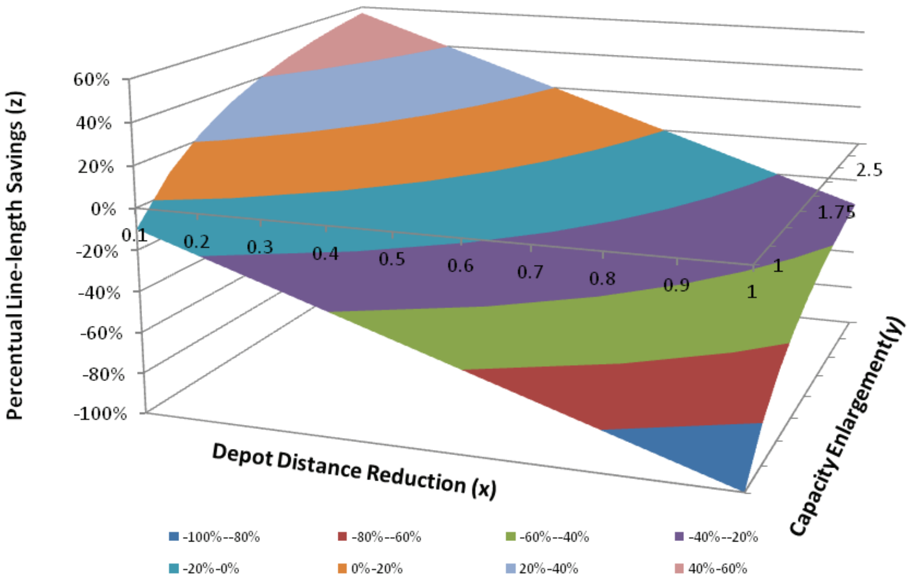

Fig. 3. Line-haul distance savings in percentage depending on the value of the parameters k_ρ, k_C (Depot distance reduction, capacity enlargement)

4. General results and case study

The model presented in the previous section will be applied to a wide variety of ranges of values to analyze the results. This will show the effectiveness of the Consolidation Center (CC) for the ranges of values.

The following ranges of values are used in Fig. 4a: a service area between 0.4km^2 and 50 km^2 and a stores density between 1 and 250 stores/km^2. In blue tonality we find unit costs with the use of the CC. In warm colors we find costs without consolidation.

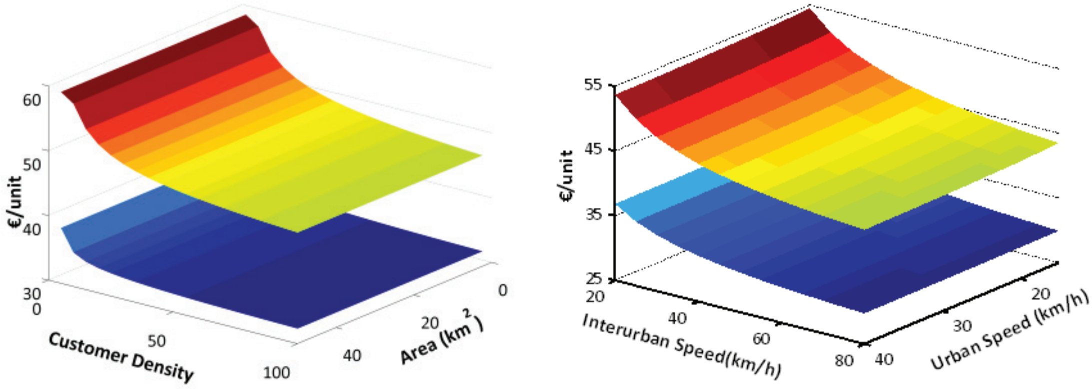

Fig. 4.(a) Unit cost of distribution depending on the area size and costumer density; (b) Unit cost of distribution depending on the distance of the closest depot

Unit cost of distribution can be reduced dramatically with the use of a CC. We can observe that as costumer density increases unit cost reduces, and that as area dimension increases so does the unit cost. We can confirm that the saving per unit is attractive to promote these types of initiatives with savings around 12-14% in operation saving costs.

In Fig. 4b different speeds for urban and interurban are analyzed, the same colors of the Fig. 4a are used for the two strategies. The effect in the cost is significant, especially interurban speed. The consolidation strategy could improve the speed of vehicles: In the line-haul distance, due the possibility of night delivery; in the local distance, due to the reduced congestion in the streets or in loading/unloading places. The effect of reducing the time lost per costumer's unloading/loading is analyzed in Fig. 5a. The linear relationship is clear.

We will consider depots located from 10 km until 200km far from the service area. In Fig. 5b, the effect of this distance is reflected in the unit cost. It is clearly lineal with the distance; however, the cost of the consolidation system grows more slowly due to the enlarged vehicle capacity in the line-haul distribution.

The total cost of the model is a weighted sum of distance and temporal costs. It is important to highlight the part that each component represents in the final cost. In the results of the sensitivity analysis an average of the cost value in percentage has been extracted. Local distance cost represents an average of 3.48%, line-haul distance cost represents an average of 59.10%, and time costs an average of 37.41% of the total cost.

The city council of l'Hospitalet de Llobregat (Spain) has expressed its interest in testing the potential improvements in a pilot test: the reduction in operation costs, the number of transportation vehicles in the area, congestion, pollution, noise, etc. so the proposed methodology has been applied to define the optimal system and its benefits.

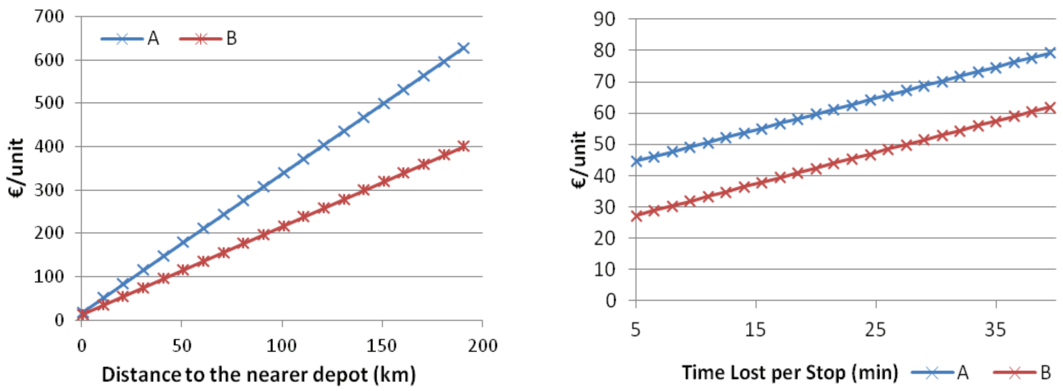

Fig. 5. (a) Unit cost of distribution depending on the time lost per stop; (b) Unit cost of distribution depending on the distance of the closest depot

The main commercial area, the most congested and with narrow streets of L'Hospitalet de Llobregat can be roughly delimited by a rectangular zone of approximately 0.64km^2. We consider that the city center is ρ=10 km far from the closest depot. But the CC can be built on the perimeter on the area, so ϕ=0.08. Regarding trucks, we assume that the average capacity is 3 Tn of Gross Vehicle Weight (GVW) for urban delivery (Madrid Municipality, 2004). With the CC we assume that the capacity will be on the average of 5.4 Tn. The defining parameters of the zone are summarized in Table 4.

Table 4. Summary of the most important metrics of the model with consolidation

Parameters	Values	Units	Parameters	Values	Units
A	0.64	[km^2]	c_d	0.3	[€/km]
ρ	10	[km]	c_t	26.36	[€/h]
v_A	25	[km/h]	k_C	1.8	[-]
v_B	50	[km/h]	k_ρ	0.08	[-]
Y	12	[h]			

Different types of establishments exist, which can be classified in: personal consume (A), hospitality and catering (B), leisure (C), construction or home materials (D), collective establishments (E), food stores (F), and others (G). We assume that each transport carrier only serves one of these types of establishments, so the savings analysis will be done separately. The city council of L'Hospitalet de Llobregat provided us with the number of stores of each type (Table 5). Table 5 has been completed using the information in the surveys of Madrid (Madrid Municipality, 2004) and (Prointec, 1997). For each type of establishment we have collected the following data: the average shipments received, the number of transport companies in the area, the number of companies participating in the CC (M), the demand per company ($\widehat{N}$), the total demand in the area, the store density, and the stops per trip. (Note that stops per trip are equivalent to capacity).

Table 5. Basic features of the stores in L'Hospitalet de Llobregat

Code	Stores	Shipments	Companies	M	$\hat{N}$	N	δ	Stops (C)
A	80	2.5	52	11	4	43	67	7
B	126	2.7	51	11	7	74	115	7
C	128	2.5	14	3	23	69	107	10
D	133	5.3	28	6	25	151	236	15
E	136	1.9	30	6	9	52	81	4
F	154	2.2	53	11	6	71	111	15
G	252	1.9	30	6	16	97	151	4

The results are presented in Fig. 6, depending on the percentage of companies participating in the CC it can be achieved between a 10 and 12% of savings in percentage comparing to the current situation. We compare the total savings with an estimated cost for the CC. The cost should cover for the infrastructural cost (rent, improvements, and maintenance), terminal personnel cost, technical machines, and information technologies. For this case study, we obtain that with the participation of transport carriers that serve the 40% of the demand, operational cost savings can be around 5% including the funding of the operation costs in the CC.

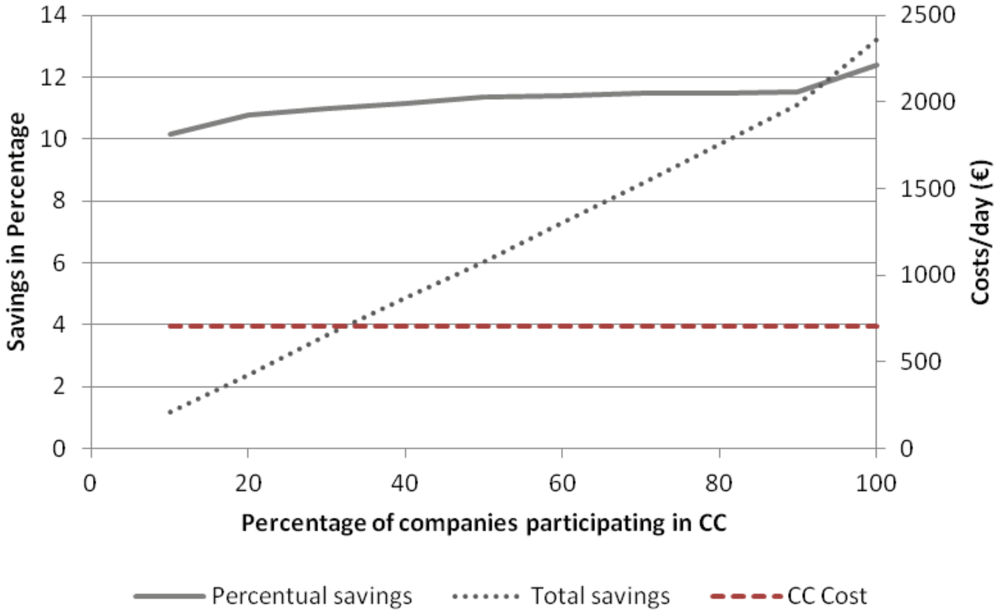

Fig. 6. Results for L'Hospitalet de Llobregat

5. Conclusion and future work

In this work we have proposed a model that uses a consolidation center to reduce operational costs in urban distribution. The methodology proposed in this work can be easily applied to a wide variety of service areas and obtain accurate approximations of the benefits. Moreover, the sensitive analysis gives a better understanding of the tendencies with the evolution of the parameters.

The results we have obtained highlight the benefits of the consolidation center in this urban context and present in detail all the metrics directly involved: costs, distance and time; and approximate indirectly savings in emissions or other environmental impacts. The results are clearly differentiated from Kawamura (2007), due to the differences in the model hypothesis. The general results are promising in the general case, with cost savings between 12-14%. In the case study of L'Hospitalet de Llobregat, we need approximately 40% of transport companies committed in the collaborative strategy to cover the CC costs.

Some assumptions can be relaxed extending the model with new parameters and/or variables. For instance, we assumed that the market was equally distributed in transport companies of the same size. We can consider the participation of different size companies in the consolidation strategy. We can also consider that some of the shipments have time window constraints and extend the formulation to accommodate the distribution. Other related work is about behavioral of the stakeholders. Design the sharing of costs and benefits among the stakeholders in order to guarantee the consensus.

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