DOES SIZE REALLY MATTER? DUAL DISTRIBUTION CHANNEL WITH VANS AND AUTONOMOUS DELIVERY DEVICES

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ABSTRACT

E-commerce sales worldwide are expected to skyrocket in future years, increasing freight traffic in cities. In this context, sidewalk autonomous delivery devices (ADDs) show great potentialities to decrease carriers' last-mile operation costs. Nevertheless, the implementation of these autonomous robots requires some adjustments in the supply chain because of their particular characteristics. To avoid severe accidents with pedestrians, their speed and size will be limited and, as a consequence, ADDs seem more adapted to the delivery of small items. The objective of this paper is to estimate the carrier's total operation costs in a dual delivery channel. If its size is lower than a given threshold, the parcel is delivered to the customer through a supply chain compound of a logistics micro-hub and ADDs. Otherwise, if the parcel is bigger than the given threshold, it is delivered through a business-as-usual supply chain with delivery vans. The carrier's total operation costs is the sum of the costs induced by the two distribution channels. Assuming that the parcel size follows a known probability distribution function, the carrier's total operation costs are estimated using the continuous approximation methodology. Different probability distribution functions modelling the size of the parcels are studied in the paper. Finally, the dual distribution channel is optimized considering the size threshold as a decision variable of the system.

1. INTRODUCTION

Freight vehicles represent around 20% of traffic in cities (Russo and Comi, 2012). Last-mile operations in dense urban environments is a major concern for carriers and logistics service providers. The rise of e-commerce is likely to worsen this situation if no measures are taken. To address these challenges and decrease last-mile operation costs, autonomous delivery devices (ADDs) could be used in future years (Figliozzi and Jennings, 2020). Nevertheless, because ADDs are medium-size vehicles that are only able to deliver small items, a dual supply chain (SC) that depends on the parcel size has to be implemented. The main objective of this paper is to quantify the carrier's total operation costs in this dual SC and compare them with the business-as-usual (BAU) deliveries.

2. OPERATION COSTS MODELLING

The continuous approximation methodology (Daganzo, 1984) will be used. The carrier's job is to deliver the parcels that are in its distribution center (DC) to final customers (see Fig. 1). The distance between the carrier's DC and the center of the service region is ρ_{DC} (see Fig. 1). In this process, the total operation costs have to be minimized. This is a particular instance of the vehicle routing problem.

2.1 Model description

A uniform demand density δ (expressed in receivers/km^2/day) is served in a service region of area A. The parcel volume stochastic variable y follows a probability distribution function (PDF) $f(y)$ (see Fig. 1). If its volume is superior to a given threshold y_{lim}, the parcel passes through a supply chain (SC) with conventional light commercial vehicles (LCVs). This is the first supply chain SC1 (see Fig. 1). On the contrary, if its volume is inferior to y_{lim}, the parcel is taken from the carrier's distribution center (DC) to a micro-hub located within the service region. Then, some ADDs perform the delivery to the final receiver. This is the second supply chain SC2 (see Fig. 1).

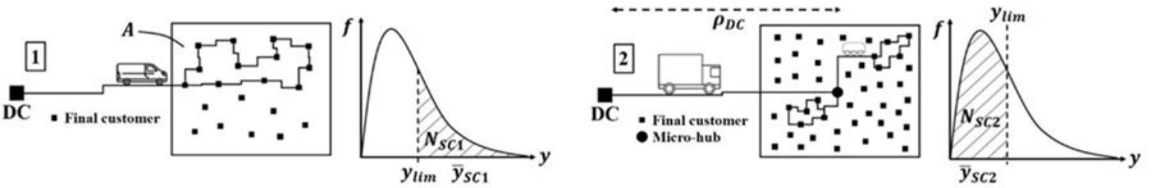


Fig. 1 – Dual SC with HDVs, LCVs and ADDs

We consider that N_{SC1} parcels with an expected volume $\bar{y}_{SC1}$ are delivered through SC1. Similar variables are denoted for the SC2 Scenario. In SC2, we assume that the parcels are carried from the carrier's DC to the micro-hub with heavy-duty vehicles (HDVs) to maximize the economies of scale. The expressions of N_{SC1}, N_{SC2}, $\bar{y}_{SC1}$ and $\bar{y}_{SC2}$ are given in Equations (1) and (2).

$$N_{SC1} = \left[\int_{y_{lim}}^{+\infty} f(y)dy\right]\delta A \; ; \; \bar{y}_{SC1} = \left(\int_{y_{lim}}^{+\infty} yf(y)dy\right) / \left(\int_{y_{lim}}^{+\infty} f(y)dy\right) \tag{1}$$

$$N_{SC2} = \left[\int_{0}^{y_{lim}} f(y)dy\right]\delta A \; ; \; \bar{y}_{SC2} = \left(\int_{0}^{y_{lim}} yf(y)dy\right) / \left(\int_{0}^{y_{lim}} f(y)dy\right) \tag{2}$$

2.2 SC1

The expected time spent per delivery in SC1 t_{SC1}^{d} is estimated by Equation (3) considering the work of Daganzo (1984).

$$t_{SC1}^{d} = \frac{1}{v_L^{LCV}} \frac{2}{\sqrt{3}} \sqrt{\frac{A}{N_{SC1}}} + \tau_s^{LCV} \tag{3}$$

Where v_L^{LCV} is the speed of LCVs in the local road grid and τ_s^{LCV} the LCV unit stop time, including parking and customer delivery process.

Then, the number of parcels delivered along one LCV route Ψ_{SC1}^{LCV} can be computed as

$$\Psi_{SC1}^{LCV} = min\left\{\frac{C^{LCV}}{\bar{y}_{SC1}} ; \frac{H_{SC1} - \frac{2\rho_{DC}}{v_{LH}^{LCV}}}{t_{SC1}^{d}}\right\} \tag{4}$$

Where C^{LCV} is the LCV volume capacity, ρ_{DC} the distance between the carrier's DC and the center of the service region (see Fig. 1), H_{SC1} the operation time window of SC1, and v_{LH}^{LCV} the speed of LCVs on metropolitan highways.

To estimate Ψ_{SC1}^{LCV}, two restrictions are considered: the number of parcels loaded in a LCV is limited and the LCV route duration cannot be longer than H_{SC1}.

Then, the total distance travelled on metropolitan highways D_{SC1}^{LH} (respectively in the local road grid D_{SC1}^{L}) and the total time worked by the LCV fleet T_{SC1} are computed.

$$D_{SC1}^{LH} = 2\rho_{DC}\left[\frac{N_{SC1}}{\Psi_{SC1}^{LCV}}\right]^{+} ;\ D_{SC1}^{L} = \frac{2}{\sqrt{3}}\sqrt{AN_{SC1}} ;\ T_{SC1} = \frac{D_{SC1}^{LH}}{v_{LH}^{LCV}} + \frac{D_{SC1}^{L}}{v_{L}^{LCV}} + \tau_s^{LCV} N_{SC1} \tag{5}$$

Finally, the LCV operation costs in SC1 are estimated in Equation (6), where c_t^{LCV} and c_d^{LCV} are the LCV unit time and distance operation costs.

$$Z_{SC1} = c_t^{LCV} T_{SC1} + c_d^{LCV}(D_{SC1}^{LH} + D_{SC1}^{L}) \tag{6}$$

2.3 SC2

Once the operation costs of SC1 have been modelled, let us focus on SC2 (parcels whose volume is inferior to the threshold y_{lim}).

2.3.1 From the carrier's DC to the micro-hub

The parcels are first taken from the carrier's DC to the micro-hub with HDVs (see Fig. 1). As previously, the first step is to compute the HDV capacity Ψ_{SC2}^{HDV} in Equation (7), where C^{HDV} is the HDV volume capacity and $\bar{y}_{SC2}$ the expected parcel volume in this SC2.

$$\Psi_{SC2}^{HDV} = \frac{C^{HDV}}{\bar{y}_{SC2}} \tag{7}$$

The term Ψ_{SC2}^{HDV} corresponds to the maximum number of parcels that can be loaded in the HDV at the carrier's DC. Then, the total distance travelled D_{SC2}^{HDV} and total time worked T_{SC2}^{HDV} by the HDV fleet are determined in Equation (8), where v_{LH}^{HDV} is the speed of HDVs on metropolitan highways and τ_{LU}^{HDV} the expected time needed to load and unload one HDV at the carrier's DC and micro-hub.

$$D_{SC2}^{HDV} = 2\rho_{DC}\left[\frac{N_{SC2}}{\Psi_{SC2}^{HDV}}\right]^{+} \; ; \; T_{SC2}^{HDV} = \frac{D_{SC2}^{HDV}}{v_{LH}^{HDV}} + 2\tau_{LU}^{HDV}\left[\frac{N_{SC2}}{\Psi_{SC2}^{HDV}}\right]^{+} \tag{8}$$

Finally, the HDV total operation costs in SC2 Z_{SC2}^{HDV} are presented in Equation (9), as the sum of the time-based and distance-based operation costs. The parameters c_t^{HDV} and c_d^{HDV} are the HDV unit time and distance operation costs.

$$Z_{SC2}^{HDV} = c_t^{HDV} T_{SC2}^{HDV} + c_d^{HDV} D_{SC2}^{HDV} \tag{9}$$

2.3.2 From the micro-hub to the final receiver

This is the second stage of SC2. The parcels are taken from the micro-hub to the final receivers with ADDs. The methodology presented by Daganzo (1984) will be used.

The expected distance between the micro-hub and the locations of the visited points ρ_h is assumed to be $\rho_h = \frac{\sqrt{A}}{2}$, where A is the total area of the service region. We assume that the logistic micro-hub is located in the center of the service region, and we define an expected distance d_{SC2}^{d} and expected time t_{SC2}^{d} per parcel delivery (see Equation 10).

$$d_{SC2}^{d} = \frac{2}{\sqrt{3}}\sqrt{\frac{A}{N_{SC2}}} \; ; \; t_{SC2}^{d} = \frac{1}{v^{ADD}}\frac{2}{\sqrt{3}}\sqrt{\frac{A}{N_{SC2}}} + \tau_s^{ADD} \tag{10}$$

Where v^{ADD} is the ADD speed and τ_s^{ADD} the ADD expected unit stop time per parcel delivery to give the parcel to the final customer. We can now estimate the expected number of parcels delivered along one ADD route Ψ_{SC2}^{ADD} by Equation (11)

$$\Psi_{SC2}^{ADD} = min\left\{\frac{C^{ADD}}{\bar{y}_{SC2}}; \frac{H_{SC2} - \frac{2\rho_{DC}}{v_{LH}^{HDV}} - \tau_{LU}^{HDV} - \frac{2\rho_h}{v^{ADD}}}{t_{SC2}^{d}}; \frac{L_b^{ADD} - 2\rho_h}{d_{SC2}^{d}}\right\} \tag{11}$$

Where C^{ADD} is the ADD volume capacity, H_{SC2} the SC2 operation time window, v_{LH}^{HDV} the speed of HDVs on metropolitan highways, τ_{LU}^{HDV} the HDV loading/unloading time at the micro-hub and L_b^{ADD} the maximum distance that an ADD can travel considering its limited battery capacity restriction.

In addition to the volume and time horizon restrictions, we also need to consider the ADD limited range (because of the robot limited battery capacity) in this SC2. Thanks to the expression of Ψ_{SC2}^{ADD}, we are able to define the total distance D_{SC2}^{ADD} and total time worked T_{SC2}^{ADD} by the ADD fleet in Equation (12). This Equation is valid only if the following consition is met (Robusté et al., 1990): $7 < \Psi_{SC2}^{ADD} < 1.5\left(\frac{N_{SC2}}{\Psi_{SC2}^{ADD}}\right)$.

$$D_{SC2}^{ADD} = 2\rho_h \left[\frac{N_{SC2}}{\Psi_{SC2}^{ADD}}\right]^+ + \frac{2}{\sqrt{3}}\sqrt{AN_{SC2}}\ ;\ T_{SC2}^{ADD} = \frac{D_{SC2}^{ADD}}{v^{ADD}} + \tau_s^{ADD} N_{SC2} \tag{12}$$

We now compute the operation costs induced by the ADD fleet in SC2 Z_{SC2}^{ADD}, by Equaiton (13), where c_t^{ADD} and c_d^{ADD} are the ADD unit time and distance operation costs.

$$Z_{SC2}^{ADD} = c_t^{ADD} T_{SC2}^{ADD} + c_d^{ADD} D_{SC2}^{ADD} \tag{13}$$

2.3.3 SC2 total operation costs

We obtain the SC2 total operation costs Z_{SC2} aggregating the HDV, ADD and micro-hub operation costs, by Equation (14), where Ω_h is the micro-hub daily operation costs.

$$Z_{SC2} = Z_{SC2}^{HDV} + Z_{SC2}^{ADD} + \Omega_h \tag{14}$$

3. NUMERICAL USE CASE

3.1 Input parameters

Different parcel volume PDFs will be considered in this paper (see Fig. 2).

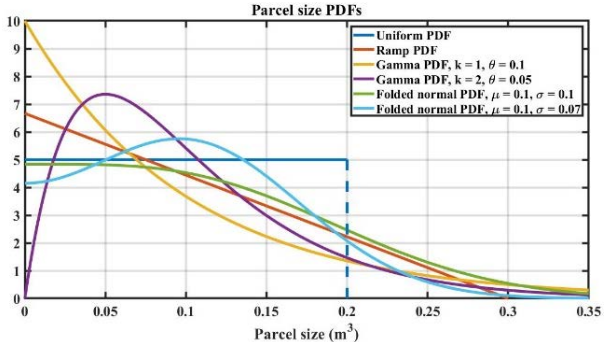


Fig. 2 – Parcel volume PDFs

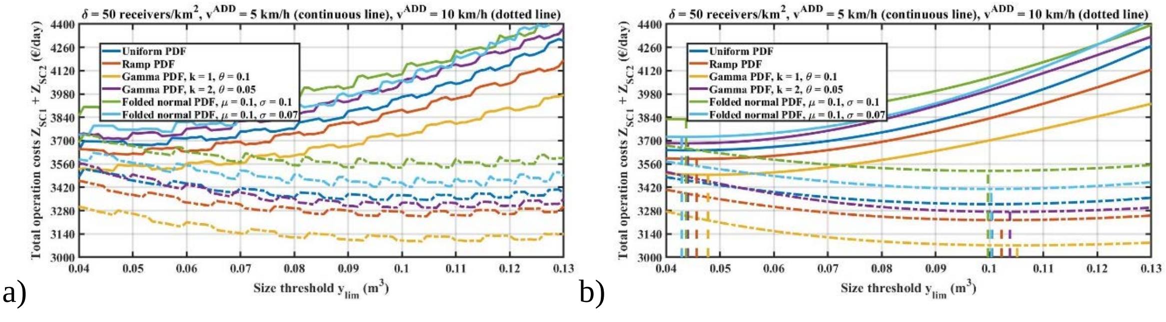
We built the PDFs presented in Fig. 2 considering the standard boxes available in-store at FedEx Office (FedEx, 2021) and assuming small parcels represent the biggest trade volume. For comparison purposes, the PDFs have the same expected parcel volume $\bar{y}$ = 0.1 m^3. The other input parameters are A = 50 km^2, ρ_{DC} = 20 km, $H_{SC1} = H_{SC2}$ = 8 h, Ω_h = 68 EUR/day, v_{LH}^{LCV} = 70 km/h, v_L^{LCV} = 20 km/h, τ_s^{LCV} = 2 min, C^{LCV} = 5 m^3, c_t^{LCV}= € 24/veh-h, c_d^{LCV}= € 0.2/veh-km, v_{LH}^{HDV} = 60 km/h, τ_{LU}^{HDV} = 30 min, C^{HDV} = 10 m^3, c_t^{HDV} = € 25/veh-h, c_d^{HDV}= €

0.3/veh-km, v^{ADD} = 5-10 km/h, τ_s^{ADD} = 1 min, C^{ADD} = 0.5 m^3, L_b^{ADD} = 50 km, c_t^{ADD} = € 5/veh-h and c_d^{ADD} = c€ 0.8/veh-km.

A service region of area A = 50 km^2 approximately corresponds to the city of Barcelona. We estimated the micro-hub daily operation costs Ω_h based on the work done by Estrada & Roca-Riu (2017). The ADD unit stop time τ_s^{ADD} is twice lower as τ_s^{LCV} because ADDs do not have to look for a parking spot and park. Then can access final customers more easily. We estimated the LCV (respectively HDV) unit time and distance operation costs c_t^{LCV} and c_d^{LCV} (respectively c_t^{HDV} and c_d^{HDV}) using data from the Observatory of Road Freight Transport in Catalonia (2019). To compute the ADD unit distance operation cost c_d^{ADD}, we estimate that the robot energy consumption is around 30 Wh/km (at 5 km/h) and that 1 kWh of electricity costs € 0.25 in Spain. As for the ADD unit time operation cost c_t^{ADD}, we assume that a robot costs around € 6,000 and is linearly depreciated over 4 years (2,500 working hours per year). We estimate the ADD maintenance costs to be around 20% of the capital costs on a yearly basis, i.e. 0.2 x € 6,000 = € 1,200/year-veh = € 0.5/veh-h (still with 2,500 working hours per year). One operator is in charge of 10 ADDs, i.e. € 20/10 = € 2/ADD-h. The ADD insurance costs are assumed to be around € 2,000/ADD-year as well as the carrier's structural costs.

3.2 Results

Fig. 3 presents the total operation costs Z_{SC1} + Z_{SC2} of the dual SC as a function of the volume threshold y_{lim}. We consider the different PDFs depicted in Fig. 2 and two ADD speed: 5 km/h (continuous lines in Fig. 3) and 10 km/h (dotted lines in Fig. 3). Fig. 3a shows the outputs of the equations presented in Section 3. Some discontinuities appear in the graphs because we considered the upper integer to compute the number of LCV, HDV and ADD routes. Fig. 3b depicts the same results considering that the number of vehicle route is directly N/C, where N refers to the total number of parcels that are to be delivered and C the capacity of the vehicle. In Fig. 3, a total demand density of 50 receivers/km^2 is considered.



a) b)

Fig. 3 – Total operation costs as a function of the volume threshold y_{lim}

Two main results can be drawn from Fig. 3. First, the parcel volume PDF has an impact on the carrier’s total operation costs. The PDF that generates less operation costs is the gamma PDF with k = 1 and θ = 0.1. This result makes sense because this is the PDF for which the parcel volumes are the most “concentrated” around 0 m^3 (see Fig. 2). More parcels are delivered through SC2 and the economies of scale generated by the ADDs are increased. On the contrary, the carrier’s total operation costs are the highest when a folded normal PDF is considered. In this case, less parcels are delivered through SC2 because their volume is more uniformly distributed. There are fewer small parcels and more big parcels than in the gamma PDF. For y_{lim} = 0.1 m^3 and v^{ADD} = 10 km/h, the difference between the gamma and folded normal PDFs is around 15% (€ 3,500/day approximately for the normal folded PDF and € 3,050/day approximately for the gamma PDF, see Fig. 3b).

The second main result is that the volume threshold y_{lim} is an important decision variable of the problem and that the carrier can optimize its total operation costs. This is especially the case when v^{ADD} = 5 km/h. For a gamma PDF (μ = 0.1, σ = 0.1) and v^{ADD} = 5 km/h, when y_{lim} passes from 0.04 m^3 to 0.13 m^3, the carrier’s total operation costs are increased by 14% (from € 3,840/day to € 4,400/day). The optimal threshold y^*_{lim} for which the carrier’s total operation costs are minimum depends on the ADD speed. For v^{ADD} = 5 km/h, y^*_{lim} is around 0.045 m^3 whereas it is around 0.1 m^3 for v^{ADD} = 10 km/h (see Fig. 3b). At a higher speed, ADDs are more competitive and the carrier should deliver more parcels through SC2 to minimize its costs. At a lower speed, ADDs are not so competitive when compared to the LCVs of SC1 and the robots are only dedicated to the smallest parcels. In the rest of the section, we consider that the number of vehicle routes is a continuous function (see Fig. 3b). Fig. 4 presents the carrier’s optimized average operation costs $(z_{SC1} + z_{SC2})^*$ per parcel delivery as a function of the total demand density δ. The average operation costs correspond to the total operation costs (see Fig. 3) divided by the total number of parcels δA. Fig. 4a shows these optimized average operation costs in absolute value (as in Fig. 3). On the contrary, they are expressed as a percentage of the business-as-usual (BAU) average operation costs in Fig. 4b. The BAU scenario corresponds to the delivery of all the parcels through SC1, without using the micro-hub or the ADDs. The micro-hub daily operation costs are not considered in this BAU situation.

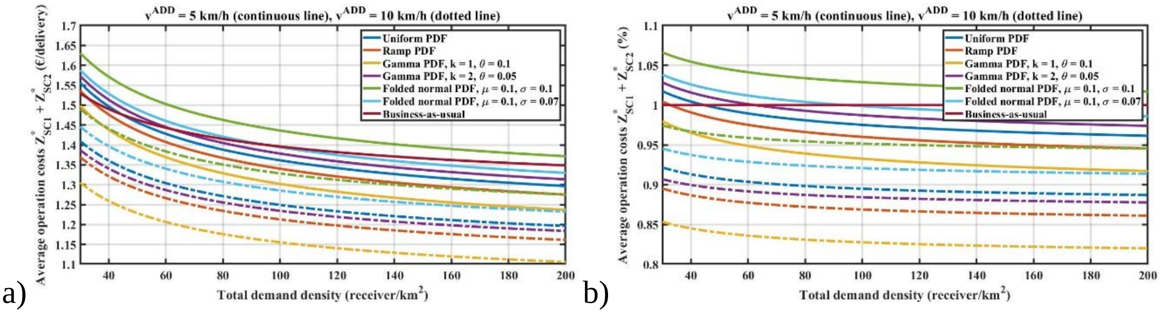


Fig. 4 – Optimized average operation costs as a function of the total demand density δ

The dual SC presents economies of scale because the average operation costs per parcel delivery decreases when the demand density increases. This is a common result is logistics operation analysis. As we observed previously, the parcel volume PDF and the ADD speed are important variables that condition the carrier's operation costs. At a demand density of 30 receivers per km^2, if the robot speed is 5 km/h, the operation costs induced by the dual SC are equal or higher (except in the case of the negative exponential PDF) than the BAU operation costs. On the contrary, if v^{ADD} = 10 km/h, the carrier's operation costs are reduced between 2% (with the worst PDF) and 15% (with the best PDF). At a higher density of 200 parcels/km^2, almost all configurations are more favorable to the dual SC. Only the combination of a normal folded PDF and a robot speed of 5 km/h generates more operation costs than the BAU delivery pattern. For v^{ADD} = 10 km/h, the cost reduction ranges from 5% to 17% depending on the considered PDF.

Finally, the optimal volume threshold y_{lim}^* as a function of the demand density δ is presented in Fig. 5.

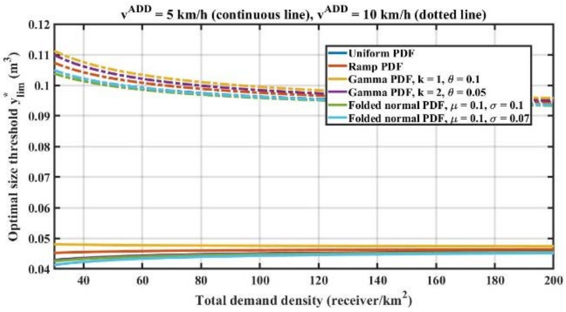


Fig. 5 – Optimized volume threshold y_{lim}^* as a function of the total demand density δ

When the robot speed is defined, y_{lim}^* is quite robust and does not depend on the demand density. For v^{ADD} = 5 km/h, the optimal threshold is around 0.045 m^3 whereas it is 0.1 m^3 when v^{ADD} = 10 km/h.

4. CONCLUSION AND FURTHER RESEARCH

In the numerical use case presented in this paper, the dual SC using ADDs could decrease the carrier's total last-mile operation costs up to 15% in the best configuration. Nevertheless, this cost reduction highly depends on the parcel volume PDF and the robot speed. If the parcel volumes are more uniformly distributed, the cost reduction is lower because less items are distributed by the ADDs. If we increase the speed of the robots, the operation cost reduction is higher because ADD operations take less time. It will be important to describe some realistic operative scenarios for ADDs in future years (circulation on secondary roads, bike lanes, sidewalks) to more precisely quantify the potential of these autonomous technologies. However, since the boom of e-commerce is expected to generate smaller parcels with higher delivery frequencies, the use of ADDs could be even more justified.

To conclude, some limitations to the developed model appear. First, the unit time and distance operation costs of ADDs are highly uncertain, which limits the representativeness of the results. Secondly, we considered that only one logistic micro-hub was implemented for a service region whose size is equivalent to the city of Barcelona. Creating a network of micro-hubs, adequately located, would certainly increase the efficiency of operations. This is left for further research.

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