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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, because their speed, size and range will be limited, 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 via a logistics micro-hub and ADDs. Otherwise, if the parcel is bigger than the given threshold, it is delivered through a conventional supply chain with delivery vans. The carrier’s total operation costs are 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.

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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 (Figliozi 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

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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), minimizing its total operation costs. The distance between the carrier’s DC and the center of the service region is $\rho_{DC}$ (see Fig. 1).

2.1. Model description

A uniform demand density $\delta$ (expressed in receivers/km$^2$/day) is served in a service region of area $A$. The parcel volume $y$ 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 distribution channel with conventional light commercial vehicles (LCVs). This is 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. Some ADDs then perform the delivery to the final receiver. This is SC2 (see Fig. 1).

![Fig. 1. Dual SC with HDVs, LCVs and ADDs.](image)

In SC1 and SC2, we assume that the different vehicles travel faster between the carrier’s DC and the service region (line-haul distance on metropolitan highways) than in the local urban grid.

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).

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

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

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).

\[
t_{SC1}^d = \frac{1}{v_{LCV}^{LCL}} \frac{2}{\sqrt{3}} \sqrt{\frac{A}{N_{SC1}}} + \tau_{LCV}^{LCL}
\]
Where $v^L_{LCV}$ is the speed of LCVs in the local road grid and $\tau^L_{Dcv}$ the LCV unit stop time, including parking and customer delivery process.

Then, the number of parcels delivered along one LCV route $\psi^L_{SC1}$ can be computed as

$$
\psi^L_{SC1} = \min \left\{ \frac{C^L_{LCV} \cdot H^L_{SC1} - 2 \rho^L_{DC} \cdot \psi^L_{LCV}}{\bar{y}^L_{SC1} \cdot t^d_{SC1}} \right\}
$$

(4)

Where $C^L_{LCV}$ is the LCV volume capacity, $H^L_{SC1}$ the operation time window of SC1, and $v^L_{LCV}$ the speed of LCVs on metropolitan highways.

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

Then, the total distance travelled on metropolitan highways $D^L_{SC1}$ (respectively in the local road grid $D^L_{SC1}$) and the total time worked by the LCV fleet $T^L_{SC1}$ are computed.

$$
D^L_{SC1} = 2 \rho^L_{DC} \left[ \frac{N^L_{SC1} \cdot \psi^L_{LCV}}{\bar{y}^L_{SC1}} \right]^{+};
D^L_{SC1} = \frac{2}{3} \sqrt{AN^L_{SC1} \cdot \tau^L_{SC1}};
T^L_{SC1} = \frac{D^L_{SC1}}{v^L_{LCV}} \cdot t^L_{LCV} + \frac{D^L_{SC1}}{v^L_{LCV}} \cdot \tau^L_{LCV} \cdot N^L_{SC1}
$$

(5)

Where $[x]^+$ stands for the upper integer of $x$.

Finally, the LCV operation costs in SC1 are estimated in Equation (6), where $c^L_{t}$ and $c^L_{d}$ are the LCV unit time and distance operation costs.

$$
Z^L_{SC1} = c^L_{t} \cdot T^L_{SC1} + c^L_{d} \cdot (D^L_{SC1} + D^L_{SC1})
$$

(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 $y^h_{lim}$).

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 $\psi^H_{SC2}$ in Equation (7), where $C^H$ is the HDV volume capacity and $\bar{y}^H_{SC2}$ the expected parcel volume in this SC2.

$$
\psi^H_{SC2} = \frac{C^H}{\bar{y}^H_{SC2}}
$$

(7)

The term $\psi^H_{SC2}$ corresponds to the maximum number of parcels that can be loaded in the HDV at the carrier’s DC. Then, the total distance travelled $D^H_{SC2}$ and total time worked $T^H_{SC2}$ by the HDV fleet are determined in Equation (8), where $v^H_{LCV}$ is the speed of HDVs on metropolitan highways and $\tau^H_{LU}$ the expected time needed to load and unload one HDV at the carrier’s DC and micro-hub.
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.

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

(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 $\rho_h$ 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 centre 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).

$$d_{SC2}^d = 2 \sqrt{\frac{A}{N_{SC2}^2}}, t_{SC2}^d = \frac{1}{v^{ADD}} 2 \sqrt{\frac{A}{N_{SC2}^2}} + \tau_{s}^{ADD}$$

(10)

Where $v^{ADD}$ is the ADD speed and $\tau_{s}^{ADD}$ 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 $\Psi_{SC2}^{ADD}$ by Equation (11).

$$\Psi_{SC2}^{ADD} = \min \left\{ \frac{C_{ADD}^{ADD} H_{SC2}^{ADD} - 2 \rho_{DC}^{ADD} v_{LU}^{HDV} - 2 \rho_b^{ADD}}{v_{ADD}^{HDV} L^{ADD}_{b}^{ADD}}, \frac{t_{SC2}^{d} - 2 \rho_b^{ADD}}{d_{SC2}^d} \right\}$$

(11)

Where $C_{ADD}^{ADD}$ is the ADD volume capacity, $H_{SC2}^{ADD}$ the SC2 operation time window, $v_{LU}^{HDV}$ the speed of HDVs on metropolitan highways, $\tau_{LU}^{HDV}$ the HDV loading/unloading time at the micro-hub and $L^{ADD}_{b}^{ADD}$ 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 $\Psi_{SC2}^{ADD}$, 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 condition is met (Robusté et al., 1990): $7 < \Psi_{SC2}^{ADD} < 1.5 \left( \frac{N_{SC2}^2}{\Psi_{SC2}^{ADD}} \right)$.

$$D_{SC2}^{ADD} = 2 \rho_b^{ADD} \left[ \frac{N_{SC2}^2}{\Psi_{SC2}^{ADD}} \right]^+, \frac{2}{\sqrt{3}} 2 \sqrt{A} N_{SC2}^{2} \Psi_{SC2}^{ADD}, T_{SC2}^{ADD} = \frac{D_{SC2}^{ADD}}{v_{ADD}^{ADD}} + \tau_{s}^{ADD} N_{SC2}^{2}$$

(12)

We now compute the operation costs induced by the ADD fleet in SC2 $Z_{SC2}^{ADD}$, by Equation (13), where $c_t^{ADD}$ and $c_d^{ADD}$ are the ADD unit time and distance operation costs.
\[ Z_{SC2}^{ADD} = c_t^{ADD} T_{SC2}^{ADD} + c_d^{ADD} D_{SC2}^{ADD} \]  

(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 \( \Omega_h \) is the micro-hub daily operation costs.

\[ Z_{SC2} = Z_{SC2}^{HDV} + Z_{SC2}^{ADD} + \Omega_h \]  

(14)

3. Numerical use case

3.1. Input parameters

Different parcel volume PDFs are considered (see Fig. 2).

![Parcels volume PDFs](image)

Fig. 2. Parcel volume PDFs.

We assume small parcels represent the biggest trade volume. For comparison purposes, the PDFs have the same expected parcel volume \( \bar{y} = 0.1 \) m\(^3\) (FedEx, 2021).

The other input parameters are \( A = 50 \) km\(^2\), \( \rho_{DC} = 20 \) km, \( H_{SC1} = H_{SC2} = 8 \) h, \( \Omega_h = 68 \) EUR/day, \( v_{LCV} = 70 \) km/h, \( v_{L}^{LCV} = 20 \) km/h, \( \tau_{L}^{LCV} = 2 \) min, \( c_{L}^{LCV} = 5 \) m\(^3\), \( c_{d}^{LCV} = 0.2 \) veh-km, \( v_{LH}^{HDV} = 60 \) km/h, \( \tau_{LU}^{HDV} = 30 \) min, \( c_{L}^{HDV} = 10 \) m\(^3\), \( c_{d}^{HDV} = 0.5 \) veh-km, \( v_{ADD} = 5-10 \) km/h, \( \tau_{L}^{ADD} = 1 \) min, \( c_{d}^{ADD} = 0.5 \) m\(^3\), \( L_{d}^{ADD} = 50 \) km, \( c_{d}^{ADD} = 5 \) veh-h and \( c_{d}^{ADD} = 0.8 \) 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 \( \Omega_h \) based on the work done by Estrada & Roca-Riu (2017). The ADD unit stop time \( \tau_{L}^{ADD} \) is twice lower as \( \tau_{d}^{LCV} \) because ADDs do not have to look for a parking spot and park, they can access final customers more easily. We estimated the LCV (respectively HDV) unit time and distance operation costs \( c_{L}^{LCV} \) and \( c_{d}^{LCV} \) (respectively \( c_{d}^{HDV} \) 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. A total demand density of 50 receivers/km² is considered.

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 $\theta = 0.1$. This result makes sense because this is the PDF for which the parcel volumes are the most “concentrated” around 0 m³ (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 (see Fig. 2). There are fewer small parcels and more big parcels than in the gamma PDF. For $y_{lim} = 0.1$ m³ 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 folded normal PDF ($\mu = 0.1$, $\sigma = 0.1$) and $v^{ADD} = 5$ km/h, when $y_{lim}$ passes from 0.04 m³ to 0.13 m³, 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 m³ whereas it is around 0.1 m³ 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 $\delta$. The average operation costs correspond to the total operation costs (see Fig. 3) divided by the total number of parcels $\delta A$. 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 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.

The dual SC presents economies of scale because the average operation costs per parcel delivery decreases when the demand density increases (see Fig. 4a). This is a common result in 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 km², 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 (see Fig. 4b). 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 receivers/km², almost all configurations are more favorable to the dual SC. Only the combination of a normal folded PDF (\( \mu = 0.1, \sigma = 0.1 \)) 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 for \( \delta = 200 \) receivers/km².

![Fig. 4. Optimized average operation costs as a function of the total demand density \( \delta \).](image)

Finally, the optimal volume threshold \( y_{lim} \) as a function of the demand density \( \delta \) is presented in Fig. 5.

![Fig. 5. Optimized volume threshold \( y_{lim} \) as a function of the total demand density \( \delta \).](image)

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 m³ whereas it is 0.1 m³ 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.

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