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Modelling the dynamics of fragmented vs. consolidated last-mile e-commerce deliveries via an agent-based model

Giovanni Calabrò[a]*, Michela Le Pira[a], Nadia Giuffrida[b], Martina Fazio[c], Giuseppe Inturri[d], Matteo Ignaccolo[a]

[a]Department of Civil Engineering and Architecture, University of Catania, Via S. Sofia 64, Catania, 95125, Italy
[b]Spatial Dynamics Lab, University College Dublin, UCD Richview Campus, D04 V1W8, Belfield, Dublin, Ireland
[c]Department of Physics and Astronomy, University of Catania, Via S. Sofia 64, Catania, 95125, Italy
[d]Department of Electric, Electronic and Computer Science Engineering, University of Catania, Via S. Sofia 64, Catania, 95125, Italy

Abstract

This paper proposes a new agent-based model (ABM) to explore different scenarios of e-commerce urban deliveries, comparing door-to-door deliveries with consolidation-based strategies. The ABM reproduces operation under different demand patterns and include the possible matching of customer systematic trips and collection/delivery points with small detour from the scheduled trip. Several variables of the model can be changed in a parametric simulation environment, allowing to infer the level of convenience of consolidation strategies for the different actors involved. The model provides indicators able to take into account customer and logistics operator perspectives, and the impact of the service on the community. Results can give useful information to understand how to manage growing on-demand urban deliveries and to measure the impact of freight transport on city sustainability.

Keywords: parcel deliveries; e-commerce; consolidation; parcel lockers; city logistics.

1. Introduction

E-commerce is a constantly growing phenomenon, becoming an increasingly common buyers' practice, also pushed by digital technologies spread. The COVID-19 outbreak has contributed to a deep change of users' habits, bringing people ever closer to the world of online shopping and increasing the related demand.

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* Corresponding author. Tel.: +39-095-7382211
E-mail address: giovanni.calabro@unict.it

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Fragmented door-to-door deliveries may not be sufficient to satisfy this rising demand nor sustainable as they can lead to different transport and delivery issues such as missed deliveries, low load factors of vehicles, increase in travel distances and related GHG emissions (Lachapelle et al., 2018). Moreover, e-commerce-related deliveries generate additional traffic in cities that hardly compensate the reduction in individual shopping trips (World Economic Forum, 2020).

This is becoming one of the big concerns of policy-makers engaged in preventing the negative impact of freight urban deliveries (Le Pira et al., 2017; Allen et al. 2018). Besides, customers can count on a faster and more reliable service compared to the recent past. In this respect, same-day and instant deliveries are two fast-growing logistics segments, although they are still not the most diffused. Deliveries should be arranged by considering demanding customers, city constraints and last-mile logistics costs, which account for most of the supply chain costs (Gevaers et al., 2011). Innovative logistics solutions could be explored to this purpose, by appropriately taking into account: (i) the impact of logistics activities on city sustainability, e.g. congestion and emissions in urban areas; (ii) the quality of service for customers, e.g. in terms of the time elapsing between the order/purchasing and the parcel delivery (lead time) that should be minimized; (iii) logistics costs, e.g. the number of vehicles needed for the deliveries, which depends on the demand and the possibility of consolidation of goods, expressed in terms of average load factor of parcel couriers vehicles and vehicle kilometres travelled (VKT).

In this paper, we present a new agent-based model (ABM) built to compare the performance of two parcel delivery strategies, namely Home Delivery and Collection-and-Delivery Point (CDP), by varying customer demand patterns, vehicle fleet capacity and the spatial density of CDPs. The first option is the most common in last-mile delivery, even if it the logistics operator must manage a fragmented delivery process, a more complex routing and higher VKT (Iwan et al., 2016). The second option includes selected locations (e.g. parcel lockers, shops) where customers can pick-up their parcels. This allows consolidating parcels, solving the expensive problem of failed deliveries and potentially reducing the impact of freight deliveries on urban traffic (Lachapelle et al., 2018). The potential of CDPs is usually related to their closeness to origin/destination of customer trips, mainly activities, services and residences. The novelty of the ABM proposed here is the simultaneous dynamic simulation of customer and freight movements with the possibility for customers to pick up their parcels in CDP along their daily trip path, considering different trip purposes. Combining passenger mobility and last mile freight deliveries through a consolidation-based approach has the potential of increasing the overall efficiency of the transport, thus turning in to one of the most promising strategies for sustainable freight transport planning. Next section will frame our research in the context of the recent research endeavours on this topic.

2. Fragmented vs. consolidated deliveries

Literature on this topic has recently started to emerge. Schnieder and West (2020) introduced the concept of Time-Area requirements, i.e. the product of the space usage and the time needed for the delivery process (including both couriers and customers movements), to evaluate the two delivery options, deriving some useful insights for policy-makers to reduce the externalities of urban deliveries. Mitrea et al. (2020) investigated the feasibility of parcel lockers and the attitude of users towards this alternative delivery solution. Authors collected useful information through a survey about the willingness to use parcel lockers instead of the traditional deliveries and the most important features that parcel must have. Regarding locations, users seem to prefer parcel lockers close to their daily origin/destination (e.g. home, workplace) so to integrate the collection of goods in their daily routine. Besides, about two third of the e-consumers are willing to deviate up to 10 minutes to collect their parcels. Van Duin et al. (2020) used three different methods for evaluating the suitability of parcel lockers in different scenarios: (i) Cost Effectiveness Analysis to calculate the delivery cost for each scenario; (ii) Multi-Criteria Analysis to identify the most important features for each alternative (e.g. safety, comfort); (iii) simulations to understand how different scenario works according to parameter set. Results show that the parcel locker solution can provide great benefits, but it requires an appropriate analysis for the identification of their optimal location. There are some very recent studies that dealt with the issue of e-commerce delivery through ABM. Le Pira et al. (2020) proposed an approach based on the integration of discrete-choice models and ABM able to simulate the propensity of users on choosing between three different e-grocery alternatives: home delivery, click-and-pick and the traditional way of shopping. Sakai et al. (2020) implemented an ABM framework, validated with real-world user's survey, to model the general e-commerce delivery demand.

Another related approach is the work of Palanca et al. (2021), where they simulated different urban mobility and delivery solutions. Alves et al. (2019) analysed different scenarios by changing the number of delivery lockers. The study integrated the use of ABM and GIS tool, and main results show that lockers can reduce the missed delivery phenomenon, generate additional monetary revenue for the supermarkets that contain them, and improve the cost effectiveness for curriers. Literature so far focused on demand analysis for different delivery strategies or configurations of deliveries based on consolidation. Our paper contributes to the literature in this field by building an ABM able to dynamically reproduce different delivery strategies and passenger movements. This is done in a parametric simulation environment to study the overall impact of the use of CDPs on the different actors involved, and specifically on the couriers routing, on the delivery cost and on the discomfort for customers, according to different demand patterns. Next section goes into the details of the methodology used to perform such analysis.

3. Methodology

The aim of the ABM is to identify the trade-off between the operator cost, the quality of service for customers and the environmental impact, considering design parameters such as the spatial density of CDPs. The ABM is implemented in the NetLogo programming environment (Wilensky, 1999) and includes four types of agents, namely customers, delivery vehicles (couriers), parcels and CDPs. A huge advantage of using ABMs is that each agent is programmed to carry out series of tasks without being necessarily aware of the status of the other agents in the system and one can study the emergence of the collective behaviour, sometimes with unexpected outcomes. The main input parameters of our simulation model concern the geometric features of the service area, the demand (customers) characterization, the supply (couriers) characteristics, and the simulation duration. We assume that delivery operations take place in a rectangular area of length L and width W. Couriers are defined by the capacity C_V (m^3), the cruise speed v_c (km/h) and the average energy consumption E_V (kWh/km) assuming they are fully electric. Operation costs are related to the drivers' wage (€$_{\mathrm{dr}}$) and vehicle cost by distance (€$_{\mathrm{dist}}$), not considering in the present work the fixed cost of vehicles. Couriers depart from a depot r distance away from the service area and travel along a grid street network (of spacing d_g). Each intersection (node) of the network could act as a potential delivery location (stop-node) where couriers stop to serve a home delivery request or a CDP. The customer demand is assumed homogeneous throughout the area, according to a demand density λ (customers /km^2-day). Customer purchase orders can be delivered either at home or in a CDP, which for simplicity is assumed to be constituted by a certain number of parcel lockers. The latter serves multiple customers, who have to go and pick-up their parcels, and are characterized by the input parameter "density of CDPs" δ (CDP/km^2). Fig. 1 presents a schematic representation of the deliveries using the two options.

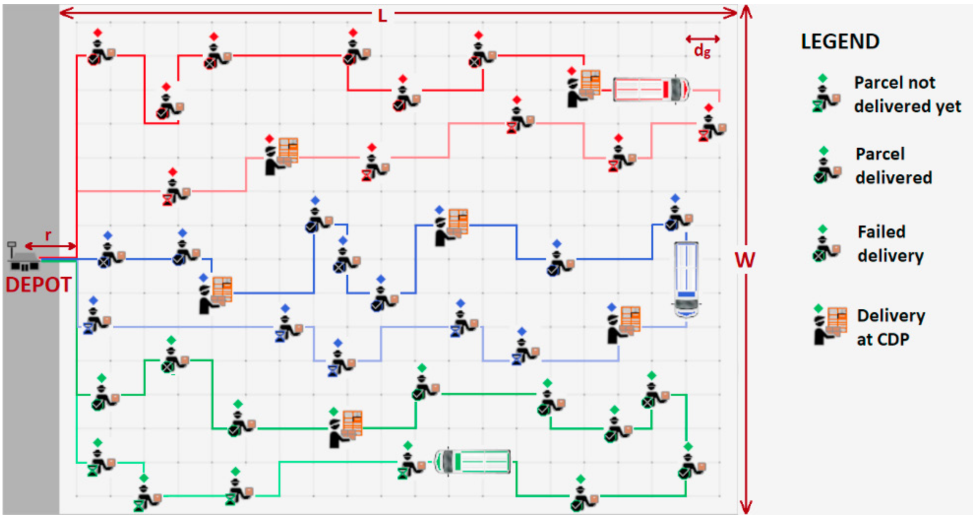

Fig. 1. Scheme of the delivery operations (Home Delivery and CDP) carried out by a fleet of couriers along the grid street network. Each courier's route is depicted in different couleurs.

The total number of deliveries in the simulated day, assuming one parcel per customer, is determined as follows:

$$N_C = \lambda \cdot L \cdot W \cdot (1 + K_R) \cdot (1 + K_F) \tag{1}$$

where K_R and K_F are coefficients accounting for the percentage of returned parcels and the percentage of failed deliveries. The latter should be calibrated based on the results of test simulations, since it depends on the previous days' delivery operations. Each customer is characterized by a different "activity profile" (as synthesized in Table 1). Customers have random origin (O) and destination (D) of their daily activities within the service region. The distance d_{OD} has thresholds based on the activity profile. There are also customers not moving from home, except for picking up (or returning) their parcel. Customers choose between four mode of transport for their trips ("*car*", "*bike*", "*PT*" (public transport) and "*walk*") and the probability P_{ij} for customer i to choose transport mode j for his trip is given by a logit model: $P_{ij} = e^{V_{ij}} / \sum_j e^{V_{ij}}$, where V_{ij} is the utility function associated with the alternative j. V_{ij} depends on the travel time t_{OD} from origin to destination, which in turn depends on the distance d_{OD}, and the alternative-specific attributes (see Table 2). In the present application, the parameters of the utility functions are taken from Cascetta (1998). We reasonably assume that customers consider as "target" CDP (possible alternative to home delivery) the one minimizing the detour time to reach it, but not exceeding the maximum detour $t_{det,max}$ (a key input parameter to be further investigated). If j = *"walk"*, the customer i can only choose the nearest CDP to the origin. If j = *"PT"*, one can also choose a CDP near to the destination. Finally, if j = *"car"* or j = *"bike"*, one can also choose a CDP near the O-D route (note that, given the same detour time, the detour distances are greater since car speed and bike speed are greater than walking speed).

Regarding customers' requests, we consider four different parcel sizes (Table 3), the percentage of which is hypothesized considering a standard courier capacity of 8 m^3 and an average number of parcels (per fully loaded vehicle) of about 150 parcels (Llorca and Moeckel, 2020). The characterization of each customer (activity profile, mode of transport, type of parcel and delivery option) is made in the "setup" phase before the simulation starts.

Table 1. Input parameters related to the activity profile of customers.

Activity profile	**Home-Work (Employee)**	**Home-Work (Self-employed)**	**Home-Shopping**	**No displacement**
O-D Distance [km]	> 0.2	> 0.2	< 5.0	0
Start travel time	7:00 ÷ 8:30	6:00 ÷ 9:00	9:00 ÷ 17:00	-
Travel time duration [hour]	6 ÷ 10	8 ÷ 10	1 ÷ 3	-

Table 2. Input parameters related to the mode of transport.

Mode of transport	**Car**	**Bike**	**PT**	**Walk**
Avg. Speed [km/h]	30	15	15	5
Utility (V)	$\beta_{t,car}\, t_{OD,car} + \beta_{c,car}\, d_{OD,car} + \beta_{0,car}$	$\beta_{t,bike}\, t_{OD,bike} + \beta_{0,bike}$	$\beta_{t,PT}\, t_{OD,PT} + \beta_{0,PT}$	$\beta_{t,}\, t_{OD,walk}$

Table 3. Input parameters related to parcels.

Parcel size	**Small (S)**	**Medium (M)**	**Large (L)**	**Extra-Large (XL)**
Percentage	40 %	40 %	15 %	5 %
Size [m^3]	0.005 m3 (0.4x0.25x0.05)	0.04 m3 (0.5x0.4x0.2)	0.12 m3 (0.8x0.5x0.3)	0.36 m3 (1x0.6x0.6)
# reserved lockers in a CDP	20	26	4	0

In order to limit the variables affecting the model, we assume that the probability for customer i of choosing the delivery at a CDP k only depend on an impedance function η_{ik} which is the ratio between the detour time to reach k and $t_{det,max}$, as below:

$$P_{ik} = (1 - \eta_{ik}) \cdot x_{CDP} = \left(1 - \frac{t_{i,k}}{t_{det,max}}\right) \cdot x_{CDP} \tag{2}$$

where x_{CDP} is a Boolean variable which assumes the value 1 if there are available lockers for the parcel and 0 otherwise. Note that, for simplicity, the detour time only includes the one-way time needed to reach the CDP, not the round-trip. It may happen that the customer choosing home delivery is not at home when the courier arrives: in this case a failed delivery occurs, if nobody else is available (a family member, a neighbour, a doorman, etc.). The probability of having an alternative person to receive the delivery is a calibration parameter, which we set assuming a percentage of failed deliveries of about 25% (Van Duin et al., 2016) when only the home delivery option is available.

The vehicle routing problem (VRP) is solved in the "setup" phase, as follows. We first determinate the minimum fleet size n_V by dividing the total volume of the parcel to be delivered $V_{del,tot}$ by the courier capacity C. Then we divide the service region into n_V rectangular sub-regions (this approximation is justified by the homogeneous spatial demand distribution), assigning the stop-nodes to serve the and estimate the travel time (including the idle time with the parked vehicle during delivery operations). In real-world scenarios, determining the optimal route assignments to the vehicles of the fleet allows the operator to obtain significant time and cost savings, so the VRP should be addressed by *ad-hoc* optimization algorithms (Calabrò et al., 2020). Since we propose a synthetic case study with an idealized grid network, we follow the guidelines suggested by Daganzo (2004) and applied in the analytical model of Quadrifoglio and Li (2009), assuming that each courier travels through the upper half of the sub-region in a no-backtracking policy (e.g. left-to-right), and then through the bottom half in a no-backtracking policy in the opposite direction (e.g. right-to-left). This pattern can be observed in Fig. 1. We consider an additional time lost at each stop $\tau_s = 30$ s, including the time of acceleration and deceleration, and average delivery times per parcel τ_p (home delivery) and τ_{cdp} (CDP).

The behaviour of the couriers and the behaviour of the customers are represented by two state charts in Fig. 2a and Fig. 2b, respectively. Every agent goes through several states, each one is activated when a given event occurs and/or if a set of conditions are met (square brackets), causing the transitions (the black arrows) between different states.

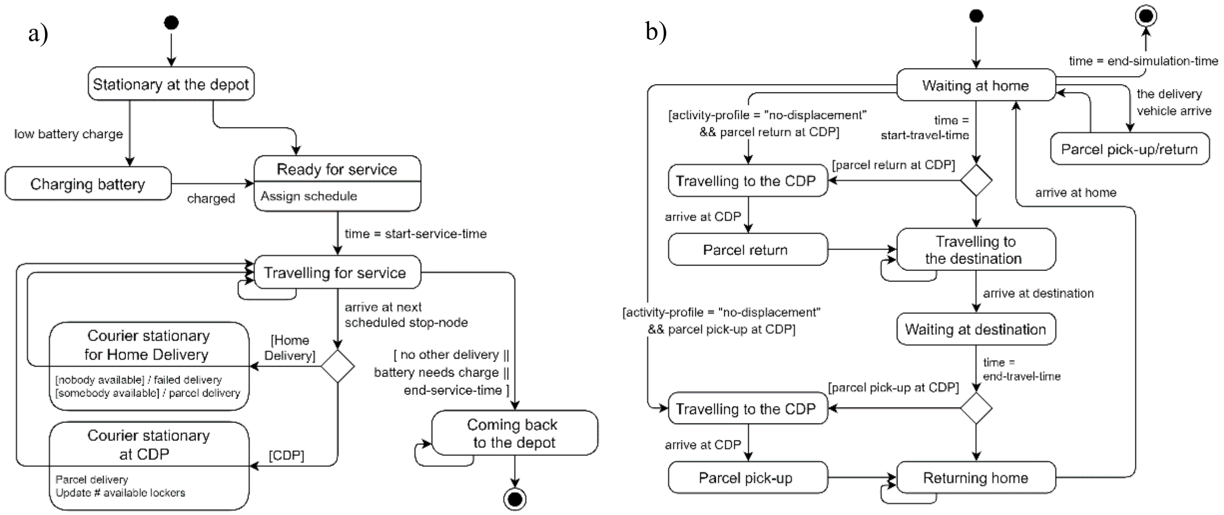

Fig. 2. (a) Courier state chart; (b) Customer state chart.

4. Preliminary results and discussion

The ABM allows monitoring of different key performance indicators, related to both customers and operators' points of view (Calabrò et al., 2021). Different scenarios can be simulated by varying the number and location of parcel lockers, courier fleet size, and customer demand patterns, allowing to infer about the attractiveness of different delivery options from the point of view of customers and logistics operators, and by evaluating the overall impact of deliveries on city sustainability.

For a first test of the model, we simulate customers' activities during an entire working day and delivery operations during 8 work hours (from 9 A.M. to 6 P.M., including a 1-hour lunch break). We applied the explained methodology to a synthetic case study that we called “Virtual-CT”. It mimics a medium-sized city (30 km^2) with a grid-like network and the freight depot in the city outskirt. Operator-related costs are taken from Llorca and Moeckel (2020). We performed two sets of simulations, by varying (1) the density of CDP and (2) customer willingness to deviate from their usual trip to reach a CDP (i.e. the max detour). The inputs of the different scenarios are reported in Table 4:

Table 4. Scenario input parameters setup.

GEOMETRIC PARAMETERS				DEMAND PARAMETERS				SUPPLY PARAMETERS							
L	W	r	**δ**	λ	K_R	v_w	**$t_{det,max}$**	n_V	C_V	v_c	τ_s	τ_p	τ_{cdp}	$€_{dr}$	$€_{dist}$
[km]	[km]	[km]	**[CDP/km^2]**	[cust/km^2]		[km/h]	**[min]**		[m^3]	[km/h]	[s]	[s]	[s]	[eur/h]	[eur/km]
6	5	1	**0-0.5-1-2-5-10**	25	0.15	5	**6 - 10**	*5-7* *	8	25	30	120	30	26.9	0.77

*The number of couriers is the minimum to satisfy the number of requests. It can vary in different simulation runs

Eleven scenarios are simulated. In particular, scenario 0 only considers home deliveries and scenarios 1-5 are related to increasing density of CDP and are repeated twice by increasing the max detour from 6 to 10 min to account for more flexibility of consumers. Specifically, scenario 1 considers a density of 0.5 CDP/km^2, scenario 2 of 1 CDP/km^2, scenario 3 of 2 CDP/km^2, scenario 4 of 5 CDP/km^2 and scenario 5 of 10 CDP/km^2. Each scenario has been run five times to test result fluctuations and have a statistics of events. Main results are reported in the following figures (Fig. 3-4-5).

Fig. 3 compares scenarios in terms of variation of customer- and operator-related outputs. In general, while increasing the density of the CDP, the percentage of customers choosing them goes up from 26% to 58%. This occurs at the expense of a small increase in their average travel time due to the detour needed, which goes from 7% to 9% (from 16 to 18 minutes) from scenario 1 to 5. From the point of view of the operator, this implies fewer costs per parcel, and higher commercial speeds due to shorter stopping times (in line with Allen et al., 2018). However, the transport intensity, which is linked to the distance travelled per parcel, and the total energy consumption do not show a clear decreasing trend. In particular, one can notice a critical value of CDP density (5 CDP/km2) after which these indicators start to get worse with respect to the previous scenarios. This suggests that, for the specific area of analysis and simulation parameters, a further increase in the CDP density would not be so beneficial in terms of distance travelled per parcel and environmental impact, meaning that there is not a meaningful consolidation effect.

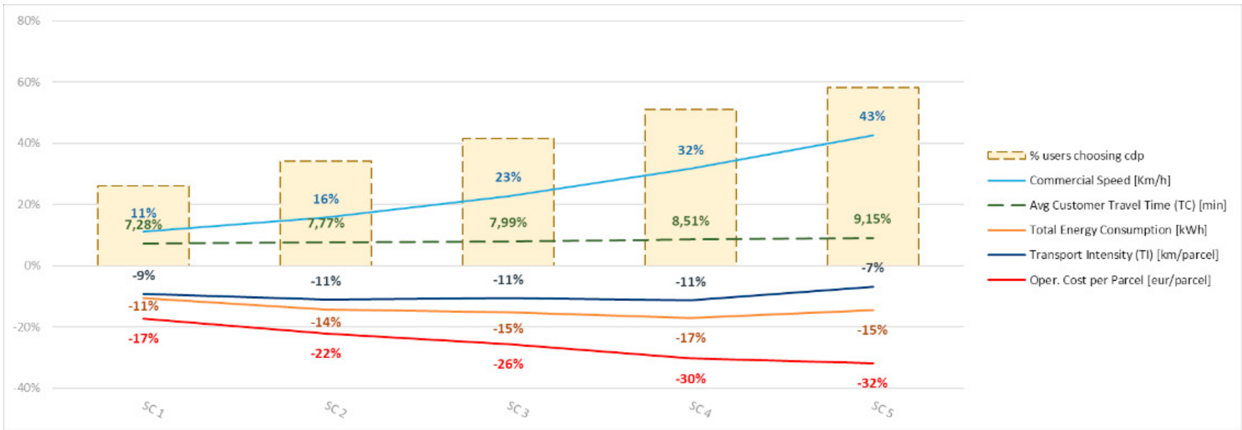

Fig. 3. Variation of customer- and operator-related outputs with respect to scenario 0 (home delivery) when increasing the CDP density (max detour time = 6 min).

If we look at failed deliveries (Fig. 4), there is a general improvement once the density of CDP increases. They drop from 22% in the scenario totally based on home deliveries (scenario 0) to 9 or 7% in the scenario with a density of CDP equal to 10 CDP/km2 (scenario 5, respectively considering a 6- or 10-minutes detour).

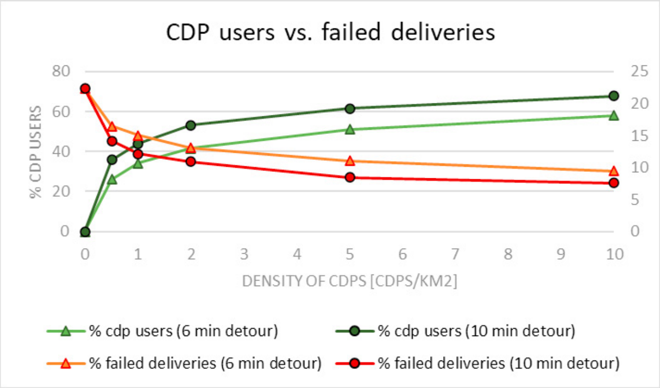

Fig. 4. %CDP users with respect to failed deliveries in the different scenarios.

Finally, when comparing scenario results obtained by increasing customer willingness to deviate from their original trip from 6 to 10 minutes (Fig. 5), one can see a small increase in the average customer travel time, and a higher benefit in terms of transport intensity, especially for CDP density equal to 2 CDP/km2.

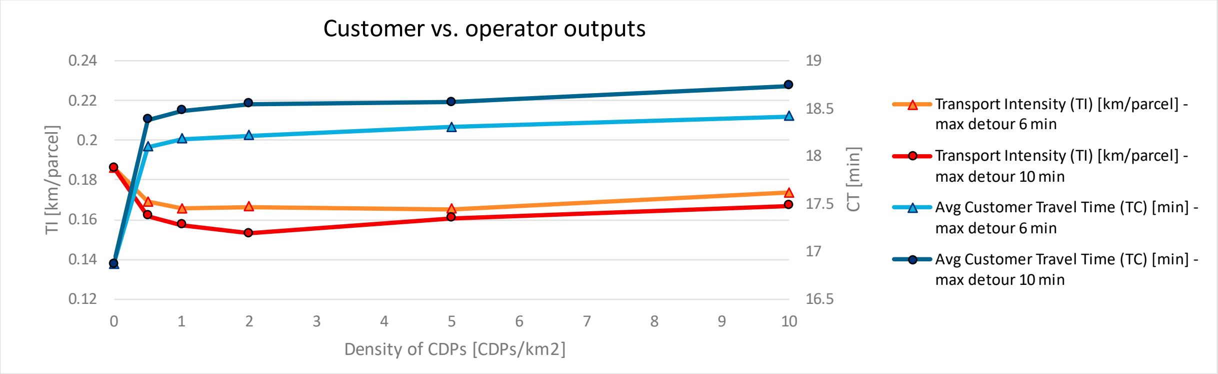

Fig. 5. Customer vs. operator outputs in terms of transport intensity (TI) and customer travel time (CTT) in the different scenarios.

To sum up, scenarios based on consolidation are to be preferred from the point of view of logistics efficiency and negative impact, even if they imply a small discomfort for the customers. The best solution from both the customer and the operator point of view (i.e. in terms of transport intensity) should be to provide a delivery service using CDP with a density from 2 to 5 CDP/km2. A mechanism of incentives for customers choosing CDP could be considered to compensate the increase in travel time due to the detour to reach the CDP.

5. Conclusions

This paper presented the first results of a new agent-based able to reproduce the complexity of on-demand last-mile parcel deliveries. These are expected to grow in the near future and are becoming a big concern for policy-makers. The model reproduces a parametric environment and is able to dynamically simulate freight deliveries and customer movements. For a first test, it is used to reproduce scenarios based on delivery consolidation via CDP.

Main results suggest that a trade-off between freight vehicle travelled distance, customer satisfaction and logistics costs can be found while proposing a solution to last mile parcel deliveries based on consolidation via parcel lockers. In particular, while increasing the density of CDP, there are more opportunities for reducing the operator costs and improving the logistics efficiency at the expense of a small discomfort for users in terms of travel time to pick up the parcel at the CDP. It is also possible to find an optimal range of CDP density implying the best results in terms of delivery impact (travelled distance per parcel and total energy consumption).

In conclusion, the proposed methodology can be used as a support tool to understand how to plan e-commerce deliveries by considering efficient solutions both from sustainability and the customer satisfaction point of view. Future research steps will focus on more tests (e.g. by simulating more than one day or different demand patterns) and to make it more realistic by reproducing real case studies with demand data.

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