Sustainable last-mile logistics with parcel lockers and autonomous delivery robots

Gianpaolo Ghiani, Emanuela Guerriero, Emanuele Manni, Deborah Pareo
Department of Engineering for Innovation, University of Salento, Lecce, Italy

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1 INTRODUCTION

The e-commerce sector is facing an unprecedented growth, with global sales expectated to surpass eight trillion dollars by 2027 (Statista, 2024). This exceptional trend has created significant challenges for the last-mile delivery industry, needing to adapt to such increasing volumes and costs, as well as to enhance efficiency and sustainability. This has led to the development of innovative solutions aimed to reduce costs, as well as the health and environmental impacts. To this end, an emerging solution in the last-mile logistics sector is the use of drop-off points, which include parcel lockers (PLs). PLs are typically unmanned facilities where customers can pick up their parcels through locked compartments equipped with technology for securely opening (e.g., secret codes, electronic keys, or mobile apps). This system enables handling more parcels per stop compared to traditional home deliveries. Moreover, it provides additional flexibility for customers, because they do not necessarily need to be at home to wait for the driver to deliver their parcels. Another emerging technology in last-mile logistics is the use of Autonomous Delivery Robots (ADRs), which are small, electric-powered vehicles capable of navigating urban environments (mainly using sidewalks) to deliver parcels to customers. Recent studies (e.g., Srinivas *et al.*, 2022) review the advantages of employing ADRs for last-mile delivery, highlighting their potential to reduce both emissions and delivery times, especially in densely populated areas.

Despite the promising results of both PLs and ADRs, very few studies have investigated the combination of these two technologies in a joint last-mile delivery model. Among these, Moradi *et al.* (2024) study a problem where trucks depart from a central depot and deliver parcels directly to either a subset of customers or parcel lockers. Customers can choose to retrieve their items from these parcel lockers if they prefer the pick-up option. Additionally, each truck is equipped with an ADR, which disembarks, serves one or more customers, and returns to the truck for battery replacement and package collection. In this context, the trucks function as mobile satellite depots for the ADRs.

In our work, we tackle this issue by proposing a delivery system that leverages both public drop-off boxes and ADRs, with the aim to reduce costs, emissions, and delivery failures. To solve this problem we make use of tailored destroy-and-repair operators within a neighborhood-search framework. We assess the benefits of the proposed last-mile delivery infrastructure, compared to traditional distribution methods. Additionally, we provide some insights about the environmental and economic advantages of using ADRs. Extensive results on a real-life scenario arising in the city of Rome, Italy, will be discussed at the conference.

2 PROBLEM DESCRIPTION

In our envisaged last-mile delivery framework, we consider an urban area infrastructured with a dense network of public PLs, managed by the municipality. In this smart-city model, direct deliveries to private residences are not allowed, with some exceptions represented by "prioritized" customers with specific requisites (e.g., elderly or disabled people), whose parcels are home-delivered by ADRs. This scheme could be beneficial from several points of view. First, consolidating deliveries at a number of PLs would result in a reduced number of stops for delivery route, thus reducing the traveled distance and lowering emissions. Moreover, this would also result in cutting logistics costs for companies, effectively eliminating the possibility of unsuccessful first-attempt deliveries. In addition, using ADRs would reduce road congestion, given that they primarily use sidewalks to move around the city. As a positive side-effect, this scheme encourages citizens to adopt a more active and healty lifestyle.

To formally describe our problem, let $G = (V, A)$ be a directed graph, in which V denotes the set of vertices and A represents the arc set. Set V is partitioned as $V = \{0\} \cup C \cup P \cup D$, where 0 is the van depot, C is the the set of customers, P is the set of parcel lockers, and D is the set of ADR depots. The set of customers C is further divided into two different subsets, C_p and C_{np}, which contain prioritized and non-prioritized customers, respectively. We assume that each customer $i \in C$ is characterized by a unit demand. In addition, when placing an order, a customer $i \in C_{np}$ specifies k alternative PLs, associating a priority to each of them. We denote as $L_i \subseteq P$ the set of PLs chosen by customer i. For prioritized customers $i \in C_p$, set L_i is constituted by the k PLs closest to their domiciles. In both cases, the private address of the customer is added to $L_i$with the lowest priority, to ensure that a feasible solution can always be obtained. Each PL $p \in P$ has a limited capacity Q_p, representing the number of lockers available for hosting parcels. At the beginning of the planning horizon, the parcels constituting customers' requests are located at depot 0, from which a fleet of vans move to take them to the PLs, from which they will be either picked-up personally by non prioritized customers, or delivered by ADRs to the private addresses of prioritized customers. The goal is to determine to which PL each request $i \in C$ should be delivered, so that either the preferences expressed by customers are maximized (if $i \in C_{np}$) or the distance traveled by ADRs is minimized (for customers $i \in C_p$). If all the preferred PLs of a request have no residual capacity, then the corresponding parcels are home-delivered by the vans during their routes.

A solution to our problem consists in: (i) assigning each request to a PL or to a private address, so to favor the assignment of lockers with the highest priority to non-prioritized customers, and those with the highest proximity to prioritized customers; (ii) routing a fleet of vans, starting from depot 0, visiting a number of PLs and (if necessary) private addresses, and returning to the depot; (iii) routing a fleet of ADRs, starting from a depot in D, visiting PLs to pick-up some parcels to be home-delivered to prioritized customers, and returning to the depot.

3 METHODOLOGY

To efficiently solve large realistic instances, starting from an initial solution, we iteratively improve it by means of a neighborhood-search approach. At each iteration, a neighborhood of the current solution is explored by employing tailored destroy-and-repair operators embedded into a neighborhood-search framework. The algorithm works as follows. Firstly, an initial solution is obtained by considering one customer request at a time and assigning it to the PL with the highest-priority for customers $i \in C_{np}$, or to the PL closest to their domicile for customers $i \in C_p$. If, for a given customer $i \in C$, all the parcel lockers $p \in L_i$ have no residual capacity, then the corresponding request is home-delivered by a van.

Destroy procedure. The destroy procedure is sketched in Algorithm 1. At each iteration, the goal is to determine a subset C' of customers for which modifying the locker assignment

Algorithm 1 Destroy phase

```
procedure Destroy($i_0$, $h$)
    iteration $\leftarrow 1$; $C' \leftarrow \emptyset$; $P' \leftarrow \emptyset$; $C'' \leftarrow \{i_0\}$        ▷ initialization
    while iteration $\leq h$ do
        $C_{\text{temp}} \leftarrow \emptyset$        ▷ temporary data structure
        for $i \in C''$ do
            $C' \leftarrow C' \cup \{i\}$        ▷ update of $C'$
            for $p \in L_i$ do
                $C_{\text{temp}} \leftarrow C_{\text{temp}} \cup \{i' \in C : p(i') = p\}$
                $P' \leftarrow P' \cup \{p\}$        ▷ update of $P'$
            end for
        end for
        $C'' \leftarrow C_{\text{temp}}$
        iteration $\leftarrow$ iteration $+ 1$        ▷ update of the iteration counter
    end while
    return ($C'$, $P'$)
end procedure
```

could potentially lead to an improving solution, as well as a subset of lockers P' to which such customers could be re-assigned. The basic idea is to identify customers that have some potential PLs in common, so that, by changing their assignments, it is likely to find improving solutions. The procedure takes as inputs a seed customer i_0, and a parameter h controlling the size of the neighborhood to be explored. Let $p(i)$ be the locker assigned to a customer $i \in C$ in the current solution. Starting with i_0, C' and P' are iteratively expanded by considering customers having lockers in common. We propose three different strategies: (i) a random choice in which all customers have the same probability of being selected (UNIFORM, in the following); (ii) a random choice in which the probabilities that customers are selected dynamically change on the basis of how frequently they have been previously included in C' (ADAPTIVE); (iii) a random choice as in UNIFORM, but the candidate customers list is restricted to contain only those who have never been in C' before (RESTRICTED, in the following).

Repair procedure. After the destroy phase, the repair operator aims to rebuild the solution by reinserting the removed elements, possibly enhancing the overall quality of the solution. To this end, we propose a binary optimization model that assigns each customer to one of the available alternatives. The decision variables are x_{ia} which are equal to 1 if $i \in C'$ is associated to alternative $a \in L_i \cap P'$, and 0 otherwise. The mathematical model is reported in the following.

$$\min \sum_{i \in C'} \sum_{a \in L_i \cap P'} w_{ia} x_{ia} \tag{1}$$

$$\text{s.t.} \sum_{a \in L_i \cap P'} x_{ia} = 1 \qquad \forall i \in C' \tag{2}$$

$$\sum_{i \in C' : a \in L_i} x_{ia} \leq Q'_a \qquad \forall a \in P' \tag{3}$$

$$x_{i_0 p(i_0)} = 0 \tag{4}$$

$$x_{i,a} \in \{0,1\} \qquad \forall i \in C', a \in P' \tag{5}$$

The objective function aims to minimize a weighted sum of the assignment variables, prioritizing customer satisfaction (i.e., assignment of a customer to the alternative with the highest priority), while penalizing van deliveries. In (1), parameter w_{ia} represents the weight of assigning customer i to alternative a. This weight is set to 0 if a is the customer's first choice, and is increased by 1 as the priority given to an option decreases. If a refers to a delivery by a van at a private address, w_{ia} is set to a reasonably high value. Constraints (2) ensure that each customer is assigned to exactly one alternative. Constraints (3) impose that the capacity of PLs is not exceeded, whereas constraint (4) prohibits reassigning customer i_0 to its original PL. Finally, constraints (5) define the domain of the variables.

As mentioned before, the sequence of destroy-and-repair operations is repeated until a stopping criterion is met, in a neighborhood-search fashion.

Table 1 – *Comparison of the three strategies for selecting the seed customer*

DATASET	INITIAL	UNIFORM		ADAPTIVE		RESTRICTED	
		OF	DEV	OF	DEV	OF	DEV
500	393.60	363.20	-7.72%	361.20	-8.23%	360.90	-8.31%
700	604.20	539.80	-10.66%	537.20	-11.09%	536.00	-11.29%
900	888.80	790.30	-11.08%	776.10	-12.68%	770.50	-13.31%

Table 2 – *Analysis of the possible* CO_2 *and cost reductions with the proposed delivery scheme*

DATASET	TRADITIONAL		ADAPTIVE			
	CO_2	COST	CO_2	COST	DEV CO_2	DEV COST
500	143.73	112.11	62.29	52.33	-56.66%	-53.32%
700	167.60	130.73	76.61	62.92	-54.29%	-51.87%
900	195.13	152.20	88.13	73.79	-54.84%	-51.52%

4 RESULTS AND DISCUSSION

In this section, we present some preliminary results, while extended computational experiments will be presented at the conference. We consider three datasets of 10 instances each, with 500, 700, and 900 customers, resembling parcel distribution in the urban area of Rome, Italy. For each dataset we consider 50 parcel lockers and 25 ADR depots. Moreover, $k = 3$. Regarding the value of h, after a preliminary tuning phase it has been set to 4. In Table 1 we report the average values of the best solutions (OF, in the table) found after 30 minutes by our algorithm considering the three strategies described before for selecting the seed customer i_0, evaluated in terms of percentage improvement (DEV, in the table) with respect to the initial solution (INITIAL, in the table), for the three classes of instances. As the table highlights, the three variants provide comparable results, with ADAPTIVE and RESTRICTED performing slightly better than UNIFORM, with average improvements over the initial solution up to about 13%.

To evaluate the impact of the proposed delivery scheme in terms of potential CO_2 and cost reductions, in Table 2 we report the emissions and cost values (CO_2 and COST, respectively) of the best solutions for both a traditional delivery scheme with conventional vans delivering parcels at customers' homes (TRADITIONAL, in the table) and the proposed delivery scheme, with the ADAPTIVE setting. For both performance measures, we compute the average percentage deviations of the ADAPTIVE solutions compared to the TRADITIONAL ones. The results confirm the potential benefits of using the proposed scheme, with emission and cost values that could be more than halved compared to the current practice.

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References

Moradi, Nima, Mafakheri, Fereshteh, & Wang, Chun. 2024. Covering Routing Problem with Robots and Parcel Lockers: A Sustainable Last-Mile Delivery Approach. *In:* A. Brown Greer, C. Contardo, J.-M. Frayret (ed), *Proceedings of the IISE Annual Conference & Expo 2024*.

Srinivas, Sharan, Ramachandiran, Surya, & Rajendran, Suchithra. 2022. Autonomous robot-driven deliveries: A review of recent developments and future directions. *Transportation Research Part E: Logistics and Transportation Review*, **165**, 102834.

Statista. 2024. *Retail e-commerce sales worldwide from 2014 to 2027*. `https://www.statista.com/statistics/379046/worldwide-retail-e-commerce-sales/`. Last accessed on: September 23, 2024.