Optimal cooperation schemes for last-mile deliveries in cities

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1 INTRODUCTION

Last-mile logistics is an area of research characterized by growing interest. This development is directly related to the increase of *e-commerce*, which has shown steady growth over the past decade, leading to new opportunities and challenges for logistics companies, including the increase in the volume of goods and number of vehicles to be handled especially in urban networks (Deloison *et al.* , 2020). Despite last-mile logistics is fundamental for the commercial activities of the city, this is also the stage of the *delivery* chain characterized by the greatest inefficiency causing up to 28% of total shipping costs (Wang *et al.* , 2016). The scenario is further complicated in case deliveries occur in historical centers, due to limited space and the presence of artistic and cultural elements (Silva *et al.* , 2023). For these reasons, policies and strategies to improve *last mile delivery* have been applied in numerous cities covering both simple modifications to traditional systems and the adoption of innovative technologies, including robots and drones, and the development of advanced algorithms (Boysen *et al.* , 2021). It is worth noting that the success of these initiatives depends on the commitment of the *stakeholders* involved and their willingness to cooperate. Indeed, a critical factor that may limit the effectiveness of these applications is the reluctance of couriers to share data and information with competitors of the same market. Therefore, it is crucial to develop a mechanism for regulating cooperation through compensations to balance possible negative effects suffered by stakeholders. An example of such cooperation is presented in Caballini *et al.* (2016), where collaborative schemes among haulers is proposed to optimize long-distance transport activities. The present work aims at analyzing and comparing different cooperative schemes for last-mile deliveries in an urban area with an historical center. For each scheme a mathematical programming model is proposed in order to find the optimal delivery solutions for a set of couriers which have to serve both the external area of the city and the historical center in which only Electric Vehicles (EVs) can enter.

2 MATHEMATICAL MODELS FOR COLLABORATIVE LOGISTICS

The problem to be addressed in this work regards a set of couriers which have to plan their deliveries in an urban area day by day. The area to be covered is composed by an external area and an historical centre where only EVs can move. Each courier has a hub in the external area of the city where parcels are collected before being delivered to the customers. Moreover, it is assumed that a common hub is present for allowing the exchange of parcels among couriers (in case there is collaboration and some deliveries belonging to a courier are realized by another one). It is indeed assumed that the collaboration among couriers can only involve the "internal" demand, i.e. the demand to be delivered in the historical centre.

Each courier has a heterogeneous fleet of vehicles, both of Internal Combustion Engine (ICE) type and EVs, with different capacities, costs and autonomies. The transport demand of each courier is expressed as an internal demand for the historical centre and a set of external services, characterized by the total weight of the parcels, the required traveling time and the covered distance. We have considered 6 cases, corresponding to different collaboration schemes, and a mathematical model has been defined for each case:

- in *Case 1* there is no cooperation among the couriers and, then, a single optimization problem is solved for each courier in order to find the minimum-cost solution for each of them;
- in *Case 2* each courier can collaborate with the others with a payment in case it delivers some parcels belonging to another courier; an optimization problem is solved for each courier in order to minimize its costs;
- in *Case 3* a centralized approach is considered, i.e. a single optimization problem is solved for the whole coalition of couriers and allows to find the best delivery solution from a system point of view; in this case, no payment is applied in case a courier delivers part of another courier's demand;
- in *Case 4*, a centralized approach is considered again, as in Case 3, but adding a constraint in the problem formulation to guarantee that each courier has an economical advantage to collaborate compared to Case 1 (its cost must be lower than the one obtained in Case 1); this allows to design a collaborative scheme that is favorable for all couriers;
- *Case 5* is similar to *Case 4* but a payment is considered for the demand exchange between couriers;
- *Case 6*, finally, is used to determine the optimal fares to be paid for exchanging the internal demand in *Case 4*; the objective function in this case is the minimization of the fares (payments for exchanging the demand) such that the collaboration among couriers is guaranteed.

For space limitations, in this abstract we will report only the mathematical programming model for Case 1, starting from the description of the parameters of the model. $\mathcal{C}$ is the set of couriers, T is the maximum time for a daily trip of a vehicle. For each courier $c \in \mathcal{C}$ the following parameters are defined: $\mathcal{S}_c^{\text{ext}}$ is the set of external services, with $0 \in \mathcal{S}_c^{\text{ext}}$ representing the trip to the internal common hub to exchange the internal demand, $\mathcal{V}_c^{\text{ICEV}}$ is the set of ICE vehicles, $\mathcal{V}_c^{\text{EV}}$ is the set of EVs, $\mathcal{V}_c = \mathcal{V}_c^{\text{ICEV}} \cup \mathcal{V}_c^{\text{EV}}$ is the set of all vehicles. For each external service $s \in \mathcal{S}_c^{\text{ext}}$ of each courier $c \in \mathcal{C}$ the parameters are: $t_{c,s}$ is the traveling time [h], $q_{c,s}$ is the weight [kg], $d_{c,s}$ is the distance [km]. For the internal demand of each courier $c \in \mathcal{C}$ the parameters are: D_c^{int} is the weight [kg], τ_c and δ_c are, respectively the time [h/kg] and distance [km/kg] for serving one weight unit of the internal demand. For each vehicle $v \in \mathcal{V}_c$ of each courier $c \in \mathcal{C}$ the parameters are: $Q_{c,v}$ is the capacity [kg], $C_{c,v}$ is the traveling cost [€/km]. Finally, for each vehicle $v \in \mathcal{V}_c^{\text{EV}}$ of each $c \in \mathcal{C}$, the autonomy $A_{c,v}$ [km] must be also considered.

The decision variables are: $y_{c,s,v} \in \{0,1\}$ is equal to 1 if service s is realized by vehicle v of courier c, 0 otherwise, $c \in \mathcal{C}$, $s \in \mathcal{S}_c^{\text{ext}}$, $v \in \mathcal{V}_c$; $x_{c,u,v}$ is the internal demand of courier c transported from the external hub to the internal common hub by vehicle u of courier c and then served in the historical centre by vehicle v of courier c [kg], $c \in \mathcal{C}$, $u, v \in \mathcal{V}_c$; $z_{c,s} \in \{0,1\}$ is equal to 1 if service s of courier c is not realized, $c \in \mathcal{C}$, $s \in \mathcal{S}_c^{\text{ext}} \setminus \{0\}$; w_c is the internal demand of courier c which is not served, with $c \in \mathcal{C}$, and which can assume values in the range $[0,\, D_c^{\text{int}}]$.

The objective function, for each courier $c \in \mathcal{C}$ is given by:

$$\sum_{s\in\mathcal{S}_c^{\text{ext}}} \sum_{v\in\mathcal{V}_c} C_{c,v} \cdot d_{c,s} \cdot y_{c,s,v} + \sum_{u\in\mathcal{V}_c} \sum_{v\in\mathcal{V}_c} C_{c,v} \cdot \delta_c \cdot x_{c,u,v} - \varepsilon \cdot \sum_{u\in\mathcal{V}_c} \sum_{v\in\mathcal{V}_c} x_{c,u,v} + N \cdot \left(w_c + \left(\sum_{s\in\mathcal{S}_c^{\text{ext}}\setminus\{0\}} z_{c,s} \right)\right) \quad (1)$$

with N being a large constant and ε a small one. Objective function (1) has been formalized with the aim of minimizing the delivery cost of a single courier and satisfying customer delivery demands. In fact, the first two terms represent the costs incurred by a courier for external services and downtown delivery, respectively, while the third and fourth terms stimulate the operator to complete all services.

This objective function is subject to constrains described below.

$$\sum_{v\in\mathcal{V}_c} y_{c,s,v} + z_{c,s} = 1 \qquad c \in \mathcal{C} \quad s \in \mathcal{S}_c^{\text{ext}} \setminus \{0\} \quad (2)$$

Constraints (2) impose that each external service, excluding the "empty" service, of the considered courier c should be assigned to a vehicle of that courier, otherwise the service is not performed and variable $z_{c,s}$ takes value equal to 1 (circumstance that is appropriately penalized in the objective function).

$$\sum_{s\in\mathcal{S}_c^{\text{ext}}} y_{c,s,v} \le 1 \qquad c \in \mathcal{C} \quad v \in \mathcal{V}_c \quad (3)$$

Constraints (3) ensure that each vehicle of courier c performs at most one external service.

$$\sum_{u\in\mathcal{V}_c} \sum_{v\in\mathcal{V}_c} x_{c,u,v} + w_c = D_c^{\text{int}} \qquad c \in \mathcal{C} \quad (4)$$

Constraints (4) define the part of the internal demand w_c which cannot be served by the courier, again this is a circumstance penalized in the objective function.

$$x_{c,u,v} \le M \cdot \sum_{s\in\mathcal{S}_c^{\text{ext}}} y_{c,s,v} \qquad c \in \mathcal{C} \quad u, v \in \mathcal{V}_c \quad (5)$$

where $M \ge D_c^{\text{int}}$. Constraints (5) are included to represent that if part of the internal demand of c is served by one of its vehicles v, i.e., $x_{c,u,v} > 0$, then it is necessary for v to be assigned a service (even the "empty" service), i.e., $\sum_{s\in\mathcal{S}_c^{\text{ext}}} y_{c,s,v} \ge 1$.

$$\sum_{s\in\mathcal{S}_c^{\text{ext}}} q_{c,s} \cdot y_{c,s,v} + \sum_{u\in\mathcal{V}_c} x_{c,v,u} \le Q_{c,v} \qquad c \in \mathcal{C} \quad v \in \mathcal{V}_c \quad (6)$$

$$\sum_{u\in\mathcal{V}_c} x_{c,u,v} \le Q_{c,v} \qquad c \in \mathcal{C} \quad v \in \mathcal{V}_c \quad (7)$$

Constraints (6)-(7) guarantee that the capacity of vehicles is respected during the execution of both external services (6) and internal services (7).

$$\sum_{u\in\mathcal{V}_c} \sum_{v\in\mathcal{V}_c^{\text{ICEV}}} x_{c,u,v} = 0 \qquad c \in \mathcal{C} \quad (8)$$

Constraints (8) ensure that the internal demand is delivered only by EVs.

$$\sum_{s \in \mathcal{S}_c^{\text{ext}}} t_{c,s} \cdot y_{c,s,v} + \sum_{u \in \mathcal{V}_c} \tau_c \cdot x_{c,u,v} \leq T \qquad c \in \mathcal{C} \quad v \in \mathcal{V}_c \tag{9}$$

Constraints (9) impose the maximum time of service for each vehicle.

$$\sum_{s \in \mathcal{S}_c^{\text{ext}}} d_{c,s} \cdot y_{c,s,v} + \sum_{u \in \mathcal{V}_c} \delta_c \cdot x_{c,u,v} \leq A_{c,v} \qquad c \in \mathcal{C} \quad v \in \mathcal{V}_c^{\text{EV}} \tag{10}$$

Constraints (10) allow for respecting the autonomy of electric vehicles.

3 THE CASE STUDY

The optimization problems introduced above have been applied to last-mile delivery processes taking place in the city of Parma in Italy. Two scenarios have been analyzed, both based on data from real case studies already published in the previous works (Tozzi *et al.* , 2014) and (Morganti & Gonzalez-Feliu, 2015). More in detail, the definition of urban goods movements in the city of Parma has been inspired by Tozzi *et al.* (2014), while Morganti & Gonzalez-Feliu (2015) suggested the definition of the parameters used to represent delivery services performed by ICE vehicles both in the external area and in the historical center.

The two scenarios considered differ in their capability to meet the delivery service in the internal area, specifically: in *Scenario a*, each courier is able to perform the delivery service in the internal area without having to cooperate with other logistics operators; in *Scenario b*, on the other hand, some couriers in the coalition do not have enough capacity in their respective electric fleet to fully meet the delivery demand in the historical center. In these scenarios, the electric vehicles used are electric vans and cargo bikes already available in the market (i.e., ONO, Urban Arrow Tender 1500, Pop-Up Mini e Goupil G2).

The problems formalized in *Cases 1-6* have been applied to this case study to determine the optimal allocation of vehicles to the volumes of goods to be transported by incentivizing the use of electric vehicles (in both *Scenario a* and *Scenario b*) and to define a cooperative scheme between couriers that allows for an improvement in the performance of each operator involved, both in terms of economics and customer satisfaction, as well as to provide a scheme that automatically determines the fares to be applied when a coalition of couriers is formed (*Scenario b*).

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