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The Grey Zone Two-Echelon Vehicle Routing Problem with Customer-to-Parcel Locations and Low-Pollution Vehicles for Inner-City Logistics

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Abstract This study addresses the two-echelon vehicle routing problem with grey zones and Customer-to-Parcel (C2P) stations. This problem arises in the search for new sustainable delivery schemes for e-commerce and last-mile distribution in urban areas and aims at reducing last-mile transportation costs. This study proposes a literature review on the subject, and a mixed integer linear programming (MILP) formulation to model and solve small instances of the described problem.

Keywords 2-Echelon vehicle routing problem · Synchronization · Customer to parcel · City logistics · Last-mile delivery · Sustainable logistics

Introduction

Last-mile logistics has gained greater importance as the demand for *Business-2-Consumer* products in urban areas has increased with the strong growth of e-commerce driven by a wider access to internet services, both for customers and for companies that buy and sell their products through this channel [1]. This generates a huge potential for consolidation and coordination of distribution flows, which play a key role in multi-echelon distribution systems [2] and can help to reduce traffic volume by improving the use of transportation resources [3]. To address last-mile particular challenges, the transition from the use of Internal Combustion Engine Vehicles (ICEV) to Alternative Fuel Vehicles (AFV), the implementation of access restrictions into urban areas and the integration of Customer-to-Parcel stations (e.g. lockers and pick-up points) have become commonly adopted measures. Therefore,

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we introduce the Grey Zone Two-Echelon Vehicle Routing Problem with Customer-to-Parcel Locations and Low-pollution Vehicles for Inner-city Logistics. Different from the classical Two-Echelon Vehicle Routing Problem (2E-VRP), clients may be served via either C2P stations or home delivery in a specified time window; furthermore we consider satellites as possible C2P stations and grey-zone customers on city borders. The contributions of this paper are threefold, as described in the following sections: First, a review of the existing literature is given in Section “Literature Review”, then Section “Problem Description and Mathematical Formulation”, defines the problem and presents a mathematical formulation to model it. Finally, the results and conclusions are given in Sections “Results” and “Conclusion and Future Research”.

Literature Review

Regarding innovative notions into 2E-VRP models intended for last-mile logistics, [6] introduced the notion of grey zones in their multi-objective problem denoted 2eVRPSyn. Customers in such zones are accessible by fleets of the two levels, giving more flexibility to their model. They proposed a large neighborhood search embedded in a heuristic rectangle/cuboid splitting to efficiently solve the problem. Moreover, [5] introduced the 2-Echelon Production Routing Problem with Cross-docking Satellites (2E-PRPCS), it features production and inventory decisions and it is solved by a Branch-and-Cut algorithm coupled with a first-solution matheuristic while [4] introduced a new variant called the Two-Echelon multiple-trip Vehicle Routing Problem with Satellite Synchronization (2E-MTVRP-SS) with time windows and service times.

On the other hand, to address e-grocery last-mile challenges, [15] proposed a Decision Support System (DSS) for a model in which the second echelon deliveries are performed through either C2P stations or electric cargo bikes.[16] developed a state of the art Hybrid Immune Algorithm (HIA) to solve a multi-objective Two-Echelon Location-Routing Problem with Mixed Vehicles and Mixed Satellites (2E-LRP-MVMS) in which the second echelon deliveries are performed through either C2P stations or Autonomous Delivery Robots (ADRs). Further, [16] modeled the Two-Echelon Vehicle Routing Problem with Mixed Vehicles (2E-VRP-MV) where Autonomous Delivery Vehicles (ADV) serve the clients in the second echelon. To solve it, a two-step clustering-based hybrid Genetic Algorithm and Particle Swarm Optimization (C-GA-PSO) algorithm are presented. Moreover, as environmental factors had gained more importance in last-mile delivery schemes, [7] introduced the 2-Echelon Electric Vehicle Routing Problem with Time Windows (2e-EVRP-TW). The model takes into account charging stations, charging times and time windows. To solve it, a heuristic based on Clarke and Wright and a Variable Neighborhood Search (VNS) are presented. For supplementary information on 2E-VRP refer to [8].

Furthermore, it was until 2018 when [9] introduced the Multi-Depot Two-Echelon Vehicle Routing Problem with Delivery Options for Last Mile Distribution (MD-

TEVRP-DO) that the concept of delivery options through C2P stations was incorporated into a 2E-VRP. Moreover, [10] proposed a Simulated Annealing Algorithm to minimize the transportation cost in their conception of 2E-VRP with locker facilities; while [11] introduced the Two-Echelon Vehicle Routing Problem with Coverage Options (2E-VRP-CO) where last mile deliveries are performed via C2P stations and cargo bikes which is then solved thanks to an Adaptive Large Neighborhood Search (ALNS). Similarly, [12] considered the synchronization of cargo bikes and vans in their two-echelon model solved by a Greedy Randomized Adaptive Search heuristic with path re-linking for real-world data of the city of Vienna. Later, [13] introduced the concept of occasional drivers in a Two-Echelon Vehicle Routing Problem with Time Windows, Coverage Options, and Occasional Drivers (a crowd-shipping concept first introduced by [14] that can provide potential advantages by its implementation). For further information on the new developments in last-mile logistics, see [17].

Problem Description and Mathematical Formulation

The problem that arises involves two different fleets of vehicles making deliveries in two different echelons. In our particular case, we consider that the vehicles start and end their routes at their respective depot. ICEVs deliver the goods from the depot of the first echelon, where the entire stock of goods is located, to the first level customers within their time windows and/or to the exchange points, also called satellites. These last are also used as Customer-to-Parcel (C2P) stations where customers can pick up their products directly. AFVs start from the second echelon depot without any goods in cargo so they must immediately meet ICEVs at the satellites where they will pick up the goods to start their deliveries. Then the AFVs serve both direct delivery customers within their respective time windows and second-level C2P stations where customers can retrieve their goods. Due to the costs associated with the use of vehicles and satellites, the waiting time of vehicles at these locations is limited to a specific value and is minimized by the inclusion of the waiting costs in the objective function (54.1) of the MILP model. For this reason, the arrival of the ICEVs and AFVs at the satellites must be approximately at the same time so that the transfer of the goods is as fast as possible and both the ICEV and the AFV can continue their deliveries. Once an AFV has finished its deliveries it can rejoin an ICEV at a satellite to retrieve new goods and continue a new route as long as the maximum route time represented by the delivery operator's working day is not exceeded. Likewise, the same satellite can be used by different AFVs as long as the ICEV's maximum waiting time at the satellite is not exceeded. In the traditional formulation of the 2E-VRP the customers of each echelon are pre-allocated to the first or second echelon, however as [6] shows, this pre-allocation can lead to poor quality results because customers close to the satellites could be served by either an ICEV or an AFV. Thus, [6] introduced the grey zone, an area in which customers are not predefined and can therefore be served by any vehicle. In this model, grey zones will be taken into account only for home

delivery customers located on the city borders. On the other hand, C2P stations are increasingly used to eliminate the risk of unattended deliveries and to optimize delivery costs thanks to the possibility of accumulating multiple demands at the same station. Similarly, these stations benefit customers by allowing them to pick up their deliveries at times that are convenient for them at stations close to their homes. Each of these stations has a specific capacity and coverage radius. The mathematical model is inspired on [6] but it considers time windows and waiting time on client nodes, C2P stations for both levels, and location decisions for satellites and stations (Table 54.1).

The objective function (54.1) takes into account the fixed cost of vehicles, the cost per distance, the vehicle operating cost per hour for each level, the cost of opening satellites and C2P stations, and the waiting costs at satellites and client nodes. The classic restrictions of the two-echelon models were formulated (i.e. restrictions on flow, exit and return to the depots, use of vehicles, and service to home-delivery customers for each level).

$$\begin{aligned} \min \sum_{i \in v^{all}} \sum_{j \in v^{all}} \sum_{k \in F} [(T(i, j) + ST(i)) * CT(k) + (Dis(i, j) * CD(k))] * X(i, j, k) + \\ \sum_{i \in v^{all}} \sum_{k \in F} W(i, k) * CT(k) + \sum_{e \in E} \sum_{j \in v^{all}} \sum_{k \in F} X(e, j, k) * FC(k) + \sum_{i \in c2p} Y(i) * CU(i) \end{aligned} \quad (54.1)$$

Also, temporal constraints have been considered to guarantee the service to the clients within their time window. Similarly, for node routing (54.2), the time between nodes, the service time, and the waiting time at satellites and at client's nodes (in case of arrival before the lower limit of the time window) have been considered. Finally, (54.3) limits the maximum duration of the routes.

$$\begin{aligned} T(j, k) \geq (T(i, k) + Time(i, j) + ST(i) + W(i, k)) - M * \\ (1 - X(i, j, k)) \quad \forall i \in v^{1,2}, j \in v^{1,2}, k \in F^{1,2} \end{aligned} \quad (54.2)$$

$$T(e^f, k) \leq TMAX \quad \forall e^f \in E^f, k \in F \quad (54.3)$$

Subsequently, constraints (54.4)–(54.6) guarantee that the vehicle load contains the demands of both home-delivery customers and C2P stations. Furthermore, capacity constraints have been formulated for all vehicles and C2P stations.

$$U(j, k) + D(j) \leq U(i, k) + M * (1 - X(i, j, k)) \forall i \in v^{all}, j \in chd, k \in F \quad (54.4)$$

$$\begin{aligned} U(j, k) + \sum_{c \in loc^2} S(c, j) * D(c) \leq U(i, k) + M * (1 - \sum_s X(i, j, k)) \\ \forall i \in v^{all}, j \in loc, k \in F^2 \end{aligned} \quad (54.5)$$

Table 54.1 Notation

Sets	
v^{all}	Set of all nodes
E/E^f	Set of the real and the cloned depots of each Echelon
$chd/chd^{0,1,2}$	Set of all home delivery clients/set of home delivery clients in the Grey Zone (0), 1st Echelon (1) and 2nd Echelon (2)
$c2p$	Set of all possible locations for lockers and satellites
sat/sat'	Set of real and cloned satellites each physical satellite (sat) is duplicated n times (once for each 2nd and Grey Zone customer).
loc	Set of possible location for lockers
$cloc/cloc^{1,2}$	Set of all $c2p$ clients/set of $c2p$ clients from the 1st (1) and 2nd Echelon (2)
$v^{0,1,2}$	Set of nodes that can be visited by all vehicles (0), only by 1st Echelon vehicles (1) and only by 2nd Echelon vehicles (2)
$F/F^{1,2}$	Fleet of all vehicles/fleet of 1st (1) and 2nd Echelon (2) vehicles
Parameters	
M	Big number/sum of all customer demands
$TMAX/WMAX$	Maximum route duration/"(TMAX/10)" as a value of the waiting time allowed at satellites
$Time/Dis(i,j)$	Travel time and distance from node (i) to node (j)
$Q(k)/QLoc(c2p)$	Capacity of vehicle (k) and capacity of the ($c2p$) station
$CT/CD(k)$	Cost of using the vehicle (k) per unit of time and distance
$CF(k)$	Fixed costs of using the vehicle (k)
$CU/Radius(c2p)$	Opening cost and Covering radius of ($c2p$) station
$ST/D(i)$	Service time and demand in node (i)
$EA/LA(chd)$	Earliest and latest arrival time to home delivery clients (chd)
Variables	
$X(i,j,k)$	Binary variable, 1 if the arc (i,j) is crossed by the vehicle (k)
$T(i,k)$	Arrival time of vehicle (k) at node (i)
$Y(c2p)$	Binary variable, 1 if the ($c2p$) station is opened, 0 otherwise
$U(i,k)$	Load of vehicle (k) at node (i)
$W(i,k)$	Waiting time of vehicle (k) at node (i)
$S(cloc,c2p)$	Binary variable, 1 if the ($c2p$) station serves the client ($cloc$)

$$\begin{aligned}
 U(j,l) + U(j,k) + \sum_{c \in cloc^1} S(c,j) * D(c) \leq U(i,k) + \\
 M * (1 - X(i,j,k)) \quad \forall i \in v^{all}, j \in sat', k \in F^1, l \in F^2
 \end{aligned} \tag{54.6}$$

Moreover, (54.7) ensure that if a satellite is used by an ICEV, it must also be used by an AFV. Likewise, the waiting times are calculated for home delivery customers and satellites, whereas (54.8) determine the maximum waiting time allowed on satellites. Finally, (54.9) ensure that vehicles do not contain cargo when returning to their

respective depot at the end of their routes, and (54.10) guarantee that AFVs do not contain any load when visiting a satellite.

$$\sum_{i \in v^{1,2}} X(i, s, k) = \sum_{j \in v^{1,2}} X(s, j, k) \quad \forall s \in sat, k \in F^{1,2} \quad (54.7)$$

$$W(s, k) \leq \sum_{j \in v^{1,2}} (X(s, j, k)) * WMAX \quad \forall s \in sat, k \in F^{1,2} \quad (54.8)$$

$$U(i, k) \leq M * (1 - X(i, e^f, k)) \quad \forall e^f \in E^f, i \in v^{1,2}, k \in F^{1,2} \quad (54.9)$$

$$U(i, k) \leq M * (1 - X(i, s, k)) \quad \forall i \in v^2, k \in F^2, s \in sat \quad (54.10)$$

Then, C2P stations constraints were defined (i.e. opening stations, allocation of customers and service at the opened ones). Subsequently (54.11) limit to one station per client and (54.12) guarantee that for opened stations, customers are within the coverage radius.

$$\sum_{j \in c2p} S(i, j) = 1 \quad \forall i \in cloc \quad (54.11)$$

$$S(i, j) * Ds(i, j) \leq R(j) \quad \forall i \in cloc, j \in c2p \quad (54.12)$$

Results

See Table 54.2.

Our model was implemented in GUROBI 10.0 coded in Python 3.8.8 and tested under an Intel(R) Core (TM) i7-VPRO CPU 2.3GHz 16 GB RAM is efficient on instances of up to 25 nodes. For all the C2P clients, the problem is first defined as an assignment problem and then a routing problem for the opened stations, which are accessible at all times (no time windows) and create more flexibility for routing. Similarly, grey zone customers add further flexibility to the model, as they can be part of any vehicle itinerary. However, home-delivery clients reduce model flexibility as their arrival times must be within their time windows. It is relevant to highlight that the definition of the maximum waiting time allowed plays a determining factor in the correct synchronization of the vehicles at the satellites and, consequently, in the route calculation. As well, it is noted that if the model does not allow vehicles to arrive before the lower limit of the time window (which generates waiting times at the customer nodes) the results tend to increase the use of vehicles, to create longer waiting times at the satellites and, in certain cases, due to the inflexibility of the problem, to end up in a non-feasible zone.

Table 54.2 Computational results

chd^0	chd^1	chd^2	F^1	F^2	sar	loc	$loc^{1/2}$	$CV^{1/2}$	v^{all}	WT	Ex.Time	Objective	GAP %
1	1	2	1	1	2	1	1/1	75/50	15	15	0.5061	2 575	0.00
1	1	2	2	2	2	1	1/1	30/10	15	45	0.8160	6 935	0.00
1	1	2	3	3	2	1	1/1	30/10	15	45	0.8755	5 680	0.00
2	2	2	1	2	2	2	2/2	50/35	20	15	275.85	4 465	0.00
2	2	2	1	2	2	2	2/2	40/20	20	15	236.41	5 335	0.00
2	2	2	1	2	2	2	2/2	35/15	20	20	96.328	6 220	0.00
3	1	2	3	3	2	2	2/2	40/20	20	15	1351.7	2 335	0.00
4	0	2	3	3	2	2	2/2	40/20	20	25	301.59	4 950	0.00
2	4	2	3	3	2	2	3/3	75/50	24	0	3982.0	5 230	0.00
4	2	2	3	3	2	2	3/3	75/50	24	-	9000.0	4 200	10.5
4	4	4	3	3	2	2	3/3	75/50	28	-	9000.0	5 900	14.4
4	4	4	3	3	2	2	3/3	50/25	28	-	9000.0	7 059	23.8
4	4	4	3	3	2	2	3/3	45/25	28	-	9000.0	7 135	23.8
4	4	4	3	3	4	2	3/3	75/50	32	-	9000.0	5 375	18.0
4	4	4	3	3	4	2	3/3	45/25	32	-	9000.0	7 135	24.9
4	4	4	3	3	4	2	3/3	50/35	32	-	9000.0	6 800	30.0

Conclusion and Future Research

Our model aims to offer a last mile delivery scheme, where the costs associated with waiting times at customer nodes and satellites are minimized through synchronization at the satellites and waiting costs reflected in the objective. Moreover, our model includes delivery options through the integration of C2P stations in addition to traditional home deliveries under time windows. Our mathematical formulation is efficient for small size instances, however due to the NP-hard nature of the problem, it is necessary to build approximate algorithms for solving large size and real-city instances to compare the performance of our model under conditions closer to those faced by real last mile delivery services.

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