Three-phase algorithm for the Two-Echelon Vehicle Routing Problem with Grey Areas, Customer-to-Parcel Stations and Low Emission Vehicles for Last Mile Deliveries

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1 Introduction

The growth of e-commerce, driven by greater access to Internet services for both customers and businesses that buy and sell their products through this channel, has generated enormous potential for consolidation and coordination of flows through multi-level distribution systems [1].In addition, to address the particular challenges of the last mile, transitioning from Internal Combustion Engine Vehicles (ICEV) to Alternative Fuel Vehicles (AFV), implementing access restrictions in densely populated areas, and integrating customer-to-package (C2P) stations are frequently adopted measures. Unlike the classical two-echelon vehicle touring problem (2E-VRP), in this study, customers can be served either at C2P stations or by home delivery within a specified time window. We consider the first echelon satellites as potential C2P stations (e.g., lockers and pickup points), and grey areas consist of customers at the borders of urban centers. The contributions of this paper are developed as follows: First, the section 2 introduces and defines the problem. The section 3 presents the mathematical formulation. Section 4 presents the three-phase algorithm used to solve the problem. Finally, preliminary results are given on section 5 and conclusions are presented on section 6.

2 Problem description

The problem considered is of the 2E-VRP type in which two different fleets ICEV/AFV start and end their routes in their respective depots. The ICEV deliver goods from the 1st echelon depot, where the global stock of goods is located, to the first echelon customers in their time windows slots as well as to the satellites. The latter are also used as C2P stations where customers can pick up their products directly. The 2nd echelon AFV leave the second echelon depot without any load. They have to pick up the merchandise directly at the satellites to start their deliveries. AFV can serve customers directly at their locations as well as at 2nd echelon C2P stations. 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 including the waiting costs in the objective function of the MILP model presented on section 3. This implies that the arrival of ICEV and AFV at the satellites must occur at approximately the same time in order to transfer goods as quickly as possible and allow both types of vehicles to continue their deliveries. Once an AFV has completed its deliveries, it can join an ICEV at a satellite to pick up new merchandise and continue a new route, as long as it does not exceed the maximum time limit.

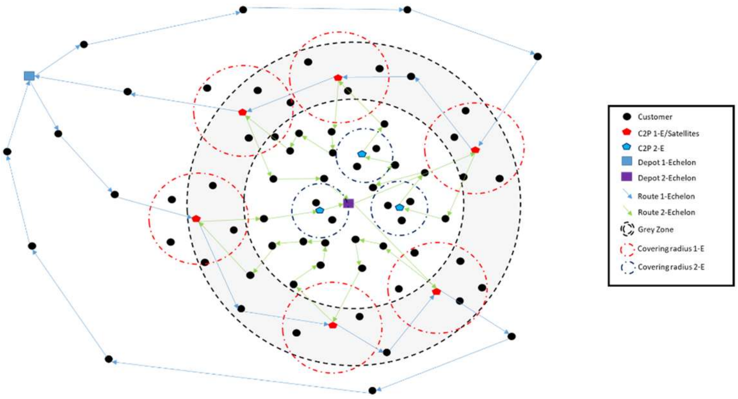


Figure 1: The 2-E VRP with Grey Areas, C2P and low emissions vehicles.

In the traditional formulation of the 2E-VRP the customers of each echelon are known in advance and therefore are pre-allocated to the first or second echelon, however as [2] 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, which can lead to reduce in part the long AFV runs outside the city center and optimizing ICEV routes and load at the city center borders. To solve this issue [2] introduced the so-called grey zone, an area in which customers are not predefined and can therefore be served by either fleet of vehicles. In our specific problem, this grey area will be considered for the allocation of home delivery customers on the routes of both levels in order to improve the quality of the solution compared to models which do not address this concept.

On the other hand, due to the increase of population density in urban areas and the development of e-commerce [3]. 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 C2P 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. For this reason, each of these stations has a specific capacity and coverage radius, where (1st echelon coverage radius is greater than the 2nd echelon coverage radius) due to the characteristics and costs of use of each echelon.

3 Mathematical formulation

The mathematical model is inspired by [2] but takes into account time windows for home deliveries; waiting time on customer nodes and C2P stations on each level; and location decisions for satellites and stations. The objective function considers fixed vehicle costs *FC*(k), variable costs per distance *CD*(k), vehicle operating cost per hour *CT*(k), satellite and C2P station opening cost *CU*(i), and satellite and customer node waiting costs *CT*(k). Where X(i,j,k) is a binary variable which value is equal to one if the arc *(i,j)* is crossed by the vehicle *k*. T(i,k)/W(i,k) represents the arrival time and the waiting time respectively of vehicle *k* at node *i* and Y(i) is a binary variable which value is equal to one if the station *i* is opened. Then, the classical constraints of two-tier models were adapted to take into account the particularities of our problem (route continuity, synchronization of the two echelons, reloading at satellites, etc.).

$$Min \sum_{i\in V^{all}} \sum_{j\in V^{all}} \sum_{k\in Fleet} \Big[\big(Time(i,j) + ServiceTime(i)\big) * CT(k) + \big(Distance(i,j) * CD(k)\big)\Big] * X(i,j,k)$$

$$+ \sum_{i\in V^{all}} \sum_{k\in Fleet} W(i,k) * CT(k) + \sum_{e\in depots} \sum_{j\in V^{all}} \sum_{k\in Fleet} X(e,j,k) * FC(k) + \sum_{i\in C2P} Y(i) * CU(i)$$

Our mixed linear programming model (MILP) was coded in Gurobi 10.0 and tested under an Intel(R) Core i7-VPRO CPU @ 2.3 GHz 16 GB RAM. The MILP model is efficient on instances of up to 15 nodes. Because of the inclusion of C2P stations on the conception of the problem, two different types of problems must be solved. First an assignment problem of customers to stations and then a routing problem for the open stations. These stations are accessible at all times during the delivery process and therefore generate more flexibility for routing. Similarly, it is important to emphasize that the definition of the maximum allowed waiting time plays a vital factor in the correct synchronization at the satellites and consequently in the calculation of routes for home delivery customers that need to be served in a specific time window. We have assumed the W_{max} as ${}^{Tmax}/_{10}$ as in [4], where T_{max} refers to the latest time allowed to end the routes.

4 Three-phase Algorithm

The method consists in three phases. The first one allocates C2P clients to the nearest C2P stations. Then the second phase creates the routes for both levels respecting the synchronization constraints at satellites. Finally, the third phase updates the arrival times of all the nodes considering the created waiting times at satellites. Our GRASP uses a randomized version of the well-known *Clarke and Wright's savings algorithm* on the second phase. A number α of savings pairs (7-10% of the savings list size) is randomly selected at the beginning of the routing process. This random selection follows a uniform probability distribution (unbiased randomization). Afterwards, a *repair algorithm* (Remove node, Best Insertion Procedure and Update Solution) verifies compliance with time windows and synchronization. Finally, local search movements are applied at each level (swap intra and inter route, relocate and crossover).

4.1 First Phase: C2P Stations Allocation Problem

The allocation algorithm selects the nearest C2P station for each C2P client of both first and second level while respecting the capacity constraints of the stations and their coverage radius.

4.2 Second Phase: 1st and 2nd Routing Problem

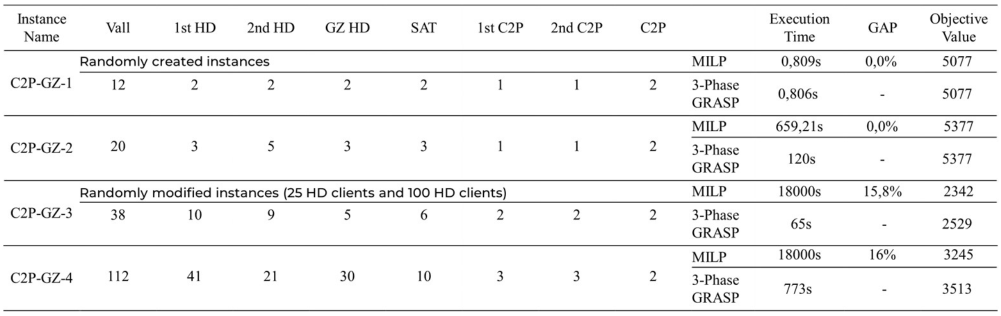
The second phase consists of three different algorithms. First a *Clarke and Wright modified savings algorithm* will create the 2nd level routes. This algorithm works like a traditional Savings algorithm by creating a savings list but will take into account time constraints by calculating time margins as done in [5], local search procedures are applied on the created routes. Then, once the 2nd echelon routes are created, a second algorithm will allocate satellites to all the established routes and, using the principle of the *saving algorithm*, will connect multiple routes. This allows vehicles to make multiple routes by reloading at different satellites provided that the maximum time duration is not exceeded. Each route merger generates the elimination of a vehicle's fixed costs. Subsequently, in order to achieve the desired synchronization at the satellites, hard time windows are fixed at these latter for the 2nd echelon routes. Then, the *Clarke and Wright modified savings algorithm*, is employed to build the 1st echelon routes. Finally, local search procedures are applied to the created routes.

4.3 Third Phase: Updating Results

Once 1st and 2nd echelon routes are created, the waiting time at satellites can be calculated and therefore the arrival time of all nodes must be updated taking into account that the waiting time at satellites has a direct impact on all the clients in routes. For this, a project management framework has been used. First, a precedence matrix is generated for all nodes, then a Gantt Priority Levels Chart is calculated and finally all the arrival times are updated following the order provided by these levels. This ensures that all precedencies will be respected and therefore all arrival times of all clients on the routes and specially on the 2nd level merged routes are consistent.

5 Preliminary results

Table 1: Preliminary results



Instance Name	Vall	1st HD	2nd HD	GZ HD	SAT	1st C2P	2nd C2P	C2P		Execution Time	GAP	Objective Value
C2P-GZ-1	Randomly created instances								MILP	0,809s	0,0%	5077
	12	2	2	2	2	1	1	2	3-Phase GRASP	0,806s	-	5077
C2P-GZ-2	20	3	5	3	3	1	1	2	MILP	659,21s	0,0%	5377
									3-Phase GRASP	120s	-	5377
C2P-GZ-3	Randomly modified instances (25 HD clients and 100 HD clients)								MILP	18000s	15,8%	2342
	38	10	9	5	6	2	2	2	3-Phase GRASP	65s	-	2529
C2P-GZ-4	112	41	21	30	10	3	3	2	MILP	18000s	16%	3245
									3-Phase GRASP	773s	-	3513

Our three-phase algorithm was tested on a randomly created small instances of 12 to 20 nodes in order to compare its results with the MILP. For small instances our algorithm was able to give the optimal solution on shorter execution time. And for modified Solomon inspired instances of 25 and 100 home delivery clients our algorithm was able to provide close solutions (7 to 9%) than the best found solution provided by Gurobi in a time limit of over 18.000s.

6 Conclusions

Our model seeks to provide a last-mile delivery scheme, where costs associated with waiting times at customer nodes and satellites are minimized through the synchronization of the routes of both echelons. In addition, our model includes delivery options via the integration of C2P stations in addition to traditional time-window home deliveries. Our mathematical formulation is effective for small instances, however due to the NP-hard nature of the problem, and in order to solve large problems we have developed a three-phase metaheuristic based on a GRASP. The results show that the algorithm is able to give similar solutions than the upper bond provided by Gurobi, nevertheless, these results could be improved by reinforcing and applying more and more adequate local search procedures on the routing phases.

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