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Abstract. In this paper we address the Two-Echelon Vehicle Routing Problem (2E-VRP), the variant of VRP where freight is delivered from depots to intermediate satellites, and then it is delivered to customers while minimizing the total routing costs of the overall Two-Echelon network. The goal of this work is to address more realistic situations in urban freight delivery where the travel costs are not only given by distances, but also by other components, like fixed costs for using the arcs, operational costs, and environmental costs. In more detail, our scope is twofold. First, we introduce a generalized travel cost able to combine the different issues (operational, environmental, congestion based). Second, we analyze how the different components of the generalized travel cost affect the satellite location in the 2E-VRP and whether the Two-Echelon approach dominates the Single-Echelon one.

Keywords. City logistics, two-echelon routing, intermediate-facility location, generalized travel cost.

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INTRODUCTION

In the Two-Echelon Vehicle Routing Problems family, the delivery from one or more depots to customers is performed in two phases; first, freight is delivered to intermediate depots, called satellites, where it is loaded on smaller vehicles, and, in a second phase, it is delivered to customers.

This approach is strongly connected to City Logistics for large urban zones (Crainic *et al.,* 2009a; Benjelloun and Crainic, 2008). Such two-tier City Logistics systems build on and expand the City Distribution Center (CDC) idea. CDCs form the first level of the system and are located on the outskirts of the urban zone. The second tier of the system is constituted of satellite platforms, where the freight coming from the CDCs and, in case, other external points may be transferred to and consolidated into vehicles adapted for utilization in urban zones. In the more advanced systems, satellites do not perform any vehicle-waiting or warehousing activities, vehicle synchronization and transdock transhipment being in use. Urban vehicles move freight to satellites, possibly by using routes specially selected to facilitate the access to the satellites and reduce the impact on traffic congestion and the environment. They may visit more than one satellite during a trip, and, at the end of their route, they are supposed to come back to the CDC. City freighters are environmental friendly vehicles of relatively small capacity which are allowed to travel along any street in the city to perform all the required distribution activities at the second level of the system. The importance of using this kind of vehicles is twofold. In fact, the pollution due to their use is very limited, contributing to improve air quality in the city centers, while their limited size allow them to reach any point in the city, also in historical cities characterized by narrow streets. This approach have been already used in several European cities with good results. The Amsterdam CityCargo system (http://www.citycargo.nl/) belongs to this class of vehicles. There are still many open issues related to this problem, including the CDC and satellite location ones (see Crainic *et al.,* 2004, in which a pioneering contribution is given and Boccia *et al.,* 2010 in which the Two-Echelon location routing problem is addressed).

In previous works, the attention was mainly focused on the minimization of the total traveled distances. Even if the distance plays a crucial role in the cost computation, it is not the only parameter which influences it. Other important parameters are the typology of the arc (highway, city center street, etc.), and the type of vehicle which cover it. Furthermore, if we also consider environmental issues, the perception of costs can sensibly change. In fact, the use of smaller environmental friend vehicles can yield to higher costs, due to the high cost technology necessary to produce these, and the usage of smaller vehicles, which increases the size of the fleet to deliver the freight. Nevertheless, in a City Logistics context we may prefer to use smaller vehicles, looking at the increment of real cost as the price to pay for a better air quality; in this case, we would assign smaller costs to this kind of vehicle, in order to promote their use. The goal of this work is to address more realistic situations in urban freight delivery where the travel costs are not only given by distances, but also by other components, like fixed costs for using the arcs, operational costs, and environmental costs. More in detail, we

want to analyze how these more comprehensive travel costs will affect the satellite location in the 2E-VRP and whether the Two-Echelon approach will dominate the Single-Echelon one and, if yes, under which conditions. In particular, it is of great interest to analyze the behavior of our approach in the case in which we want to minimize the emission of CO_2. In this case, costs of arcs cannot be considered constant in time, while they depend also on the traffic congestion, which varies on time, other than on geographical position.

We first define a generalized cost function which is given by a linear combination of different parameters: the length of the arc, the toll which may be requested for entering the arc (generally a fixed toll, not dependent on the arc length), and the travelling time, which, is dynamic. We present different sets of experiments in which we analyze different scenarios generated by varying the cost definition rule and we provide a detailed analysis on the change of satellites usage. Furthermore, we compare the Two-Echelon results with the ones obtained with the single-echelon distribution system and the impact of the typology of costs with the location issues.

PROBLEM STATEMENT

In 2E-VRP the delivery from depot to the customers is managed by routing and consolidating the freight through intermediate depots called satellites, as follows:

- freight arrives to the depot, where it is consolidated into the 1st-level vehicles;
- each 1st-level vehicle travels to a subset of satellites, and then returns to the depot;
- at each satellite, freight is transferred from 1st-level vehicles to 2nd-level vehicles;
- each 2nd-level vehicle starts from a satellite, performs a route to serve the designated customers, and then returns to the same satellite for its next cycle.

The goal is to serve customers by minimizing the total transportation cost, and satisfying the capacity constraints of the vehicles and satellites.

We consider a single depot and a fixed number of capacitated satellites. Vehicles capacity is homogeneous for vehicles operating at the same level, while it varies among levels.

Customer demands are fixed and known in advance and must be satisfied (no rejection of customers is allowed). No time windows are defined for deliveries and satellites are assumed to be available at each time of the day. The demand of each customer is supposed to be smaller than the vehicle capacity and cannot be split at any level. At the 1st level, a satellite can be served by different vehicles, which means that the aggregate satellite demand can be split.

A general time-dependent formulation with fleet synchronization and customer time windows was introduced by Crainic *et al.* (2009a) in the context of Two-Echelon City Logistics systems. The authors indicated promising algorithmic directions, but no implementation was reported.

A formal definition of Multi-Echelon VRP problems, a flow model and some valid inequalities have been presented by Perboli *et al.* (2010). Instances up to 32 customers were solved to the optimum and instances up to 50 customers solved to near optimality. The authors introduced two math-heuristics able to address instances up to 50 customers within reasonable computational time. Some of these instances have been solved by the Branch and Cut proposed in Masoero *et al.*, (2010). For what concerns heuristic methods, the fast clustering heuristic of Crainic *et al.* (2008) provides the means to address larger instances (up to 250 customers). In this method, the first and the second level are considered separately. Customers are first assigned to the nearest available satellite, then the second level problem is split into several single-depot VRPs, one for each satellite, where the satellite is considered as depot and only the customers assigned to that satellite are considered. The second level solution is used as input for the first level problem, which is treated as a split delivery VRP, where the satellites are considered as the customers of the depot. The demand of each satellite is computed as the sum of the demands of the customers assigned to it. A Multi-start heuristic presented in Crainic *et al.* (2010) allows to find good solution with a limited computational effort.

In Crainic *et al.* (2009b) a deep analysis of the layout impact on distribution costs is given. This analysis focuses on the impact of several parameters, directly correlated to the instance layout, like number of customers, number of satellites, customers distributions and satellites location. The comparison with the Single Echelon distribution approach shows that the Two-Echelon approach is strongly preferable because it allows to significantly reduce the total transportation cost, computed as the pure distance cost. Nevertheless, when the travel cost is not only given by the distance and other cost components are considered, the dominance of the Two-Echelon approach vs. the Single-Echelon one is no more so evident and this issue should be carefully analyzed.

A GENERALIZED COST FUNCTION

In this section we introduce a generalized travel cost for the arc *(i,j)* used by a vehicle type *v* in the day-hour *h*, which is given by a linear combination with coefficients α, β and γ of three different typologies of cost as follows:

$$c_{ij}^{vh} = \alpha K_{ij}^{'} + \beta K_{ij}^{''v} + \gamma K_{ij}^{'''v} t_{ij}^{h}.$$

The first cost $K_{ij}^{'}$ is a *fixed cost* related to the usage of the arc *(i,j)*, e.g. a road toll that must be paid for using that arc. Typically, if we consider a urban area, the first level arcs could be subject to road toll, while the second level ones are not. But there are some applications (like Singapore downtown) in which a high toll must be paid to access downtown in order to limit the traffic congestion in the central zone.

More in detail, tolls related to arcs connecting the CDC to a satellite, generally belonging to an highway, are much higher than tolls related to arcs connecting two depots, which may

belong to a motorway or a ring road around the city. This situation is typical of some European urban areas (and Italian in particular). Furthermore, tolls may also sensibly vary with the size of the vehicles, but, since in our problem each arc can be covered by one kind of vehicles only, we do not consider this case. The second cost represents the *operational cost*, given by the arc length d_{ij} multiplied by a parameter $K_{ij}^{''v}$, whose value depends on the vehicle type *v* and the geographical position of the arc itself. In fact, larger vehicles generally have a larger cost per km (fuel, depreciation charge, etc.) and highways and motorways, in which vehicles can maintain a constant cruise speed, have a smaller cost per km, under the same traffic conditions, with respect to city streets in which the vehicle is subject to continuous accelerations and decelerations due to traffic lights and traffic congestion.

The third term of the generalized travel cost, which can be addressed as an environmental cost, is related to the pollution emission for using arc *(i,j)* in a particular day-hour *h* and can be represented by the average travel time t_{ij}^{h} to cover the arc during day-hour *h* multiplied by a coefficient $K_{i,j}^{'''v}$ proportional to the quantity of the pollution emitted by the vehicle type *v* in a time unit while using that arc. This coefficient is influenced by both the typology of the arc (highway, main street, small street, etc.) and the typology of the vehicle.

The term t_{ij}^{h} allows us to also consider the traffic congestion, which varies over time and plays an important role in the arc cost computation. In fact, congestion is strictly time-dependent and is structured in different layers moving in concentric circles from the city center outwards and vice versa (for a deeper analysis of these aspects we refer to Stathopoulos, 2007). Values of the CO2 emission for different types of vehicle, different types of road, and different average speeds can be found in Cappiello (1998). Data on the relation between the arc traveling time t_{ij}^{h} and the level of traffic congestion can be found in ASP (2010). We consider this third term of the generalized cost function as a separate entity with respect to the second term. In fact, even if in most cases the travel time associated to an arc is linear dependent on its length, there are some cases in which it is not true. Since we identify the arc between two entities of the problem with the shortest path which connect them, this path can be composed by different kind of roads; in this case the travel time does not linearly depend on distances. Furthermore, the same arc can have different travel time in different hours of the day, even if we do not consider the traffic congestion level. In fact, traffic lights which slow down the average speed of the vehicle and consequently the travel time, generally are turned off during night hours. For all these reasons we decided to keep separate, in our generalized costs function, the term dependent on the distances and the term dependent on the travel time.

PLAN OF EXPERIMENTS

In this section we describe our plan of experiments. In order to analyze different realistic cases, we developed several scenarios, which can be grouped as follows:

1. **Analysis of distance based costs:** only the second term of the generalized cost function is considered ($\beta=1$, $\alpha=\gamma=0$). We address three different scenarios; in the first one, costs depend on the type of vehicle, in the second they depend on the arc typology (intended as arc geographical position) and in the third costs depends on both these parameters.

2. **Analysis of costs with fixed tolls:** in this case we consider ($\alpha=\beta=1$, $\gamma=0$). We address two different scenarios. In the first one, we consider high tolls for arcs connecting the depot and the satellites and small tolls for arcs between two satellites, while the second level arcs are considered free of charge. In the second case, we assign high tolls to arcs inside the city centers, while all the others are considered free of charge (Singapore's model).

3. **Analysis of different traffic conditions:** in this case all the terms of generalized cost function are taken into consideration ($\alpha=\beta=\gamma=1$). Three different scenarios have been generated, each one representing a different part of the day, early morning, early afternoon, and late afternoon.

Each scenario is composed by 9 instances, with 50 customers and 5 satellites each, characterized by a different combination of customer distribution (random, centroids, quadrants) and satellite location (random, sliced and forbidden). For more details about the instances and the related customers/satellites distributions, we refer to Crainic *et al.* (2009). The number of vehicles for the second level has been incremented by one unit in order to easily get a quite large number of feasible solutions. We used the fast clustering heuristic of Crainic *et al.* (2008) to perform our experiments. For each scenario we analyze the impact of the cost definition on the variation of total costs according to the different customer distributions and satellite locations, and we analyze how the cost definition influences the satellite usage. More details on the scenario parameters will be given in the next section.

ANALYSIS OF DISTANCE BASED COSTS

Three different scenarios S1, S2 and S3 have been generated. In S1 we consider costs depending on vehicles. A first level vehicle has a cost per km which is considered 2.5 times greater than a second level one. For that reason we have assumed that $K_{ij}^{"} = 1$ for all arcs belonging to the second level and $K_{ij}^{"} = 2.5$ for arcs belonging to the first one. If we analyze costs depending on the type of road, as in S2, the relationship among the levels is completely reversed; in fact, we consider $K_{ij}^{"} = 1$ for all arcs belonging to the first level, $K_{ij}^{"} = 1.5$ for large

streets inside the city (suburbs) and $K_{ij}^{''} = 2$ for downtown arcs. In S3 we take into account both vehicle and arc typologies assigning the following values to the parameter $K_{ij}^{''}$: $K_{ij}^{''} = 2.5$ for all arcs belonging to the first level, $K_{ij}^{''} = 1.5$ for large streets inside the city (suburbs), and $K_{ij}^{''} = 2$ for downtown arcs. All this data are taken from Cappiello (1998). In Table 1 we report the optima for each scenario and for the pure distance cost computation case, namely STANDARD, i.e. the cost obtained forcing $K_{ij}^{''} = 1$ for every arc. In Figure 1 we report a graphical view of the gap among the objective functions related to different satellite locations, letting fixed the customer distribution. On the X axes, the letters R, S and F correspond respectively to random, sliced and forbidden satellites location.

What we can immediately notice is that, for each customer distribution, the trend of the different scenarios is very similar. The lowest cost is obtained with the random distribution, while the centroid distribution yields a little bit higher cost, and the highest cost occurs in case of forbidden satellite location. These results confirm that the trend noticed on standard cost definition also holds for different distance based cost scenarios. In Table 2 we report the satellite usage for different scenarios. The satellite usage does not vary among scenarios, and variations with respect to the standard cost case occur only in 2 cases over 9 and are of small entity. Thus, the solution found is stable with respect to cost variations, which is a quite important result. In fact, to determine the exact ratio between different typology of arcs is not so trivial, because it depends on several factors varying from city to city. The stability of the solution implies that the Two-Echelon approach can be applied in different contests with similar results and a small discrepancy between real and modeled costs does not have negative effects on the best solution search.

INSTANCES	CUST	SAT	S1	S2	S3	STANDARD
Instance50-s5-37.dat	RANDOM	RANDOM	2779.03	2342.94	2854.00	1505.28
Instance50-s5-39.dat	RANDOM	SLICED	2805.34	2383.36	2919.19	1579.05
Instance50-s5-41.dat	RANDOM	FORBIDDEN	2849.30	2425.38	3077.00	1625.02
Instance50-s5-43.dat	CENTROIDS	RANDOM	2840.01	2403.58	2680.10	1599.08
Instance50-s5-45.dat	CENTROIDS	SLICED	2974.27	2503.04	2816.11	1671.81
Instance50-s5-47.dat	CENTROIDS	FORBIDDEN	3238.98	2589.78	3024.24	1784.14
Instance50-s5-49.dat	QUADRANTS	RANDOM	2856.06	2409.94	2723.23	1590.11
Instance50-s5-51.dat	QUADRANTS	SLICED	2937.71	2461.38	2833.30	1580.97
Instance50-s5-53.dat	QUADRANTS	FORBIDDEN	2776.08	2338.38	2997.79	1551.80

Table 1. Distance based cost scenario optima
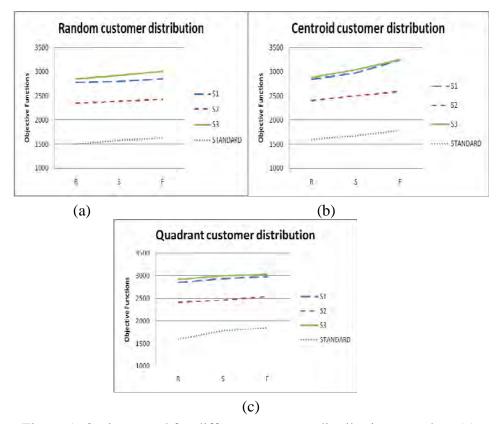
(a) (b)

(c)

Figure 1. Optima trend for different customer distributions: random (a),
centroid (b) and quadrant (c)

ANALYSIS OF COSTS WITH FIXED TOLLS

In this section we analyze cases in which a fixed toll must be paid for using some arcs. This is a very common policy in the many cities (highway, roundring tolls, city center entrance tolls, etc.). This kind of tolls is generally paid to enter a particular road or zone, and it does not depend on distance. Cases in which the toll is dependent on the distances can be treated as the scenarios presented in the previous section.

We analyze two possible scenarios: one representing a typical European city, the other one a city in which high toll must be paid for entering downtown (like Singapore). In scenario S4 we consider high tolls, $K'_{ij}=20$, for arcs connecting the depot to the satellites and smaller tolls, $K'_{ij}=5$ for arcs between two satellites, while the second level arcs are considered free of charge. In the second one, S5, downtown arcs have a fixed toll (very high) $K'_{ij}=10$ and other arcs are free of charge. Since, from the previous section, we know that the value of K''^{v}_{ij} is not so relevant, we consider $K''^{v}_{ij}=1$ for all arcs.

In Table 3, we report the satellite usage for S4 and S5. First, we can notice that, in S4, the distribution of goods is equal to the one obtained in the STANDARD case. This can be easily justified by analyzing the impact of tolls on the distribution. Direct arcs from depot to satellites have a greater cost with respect to those between satellites. This implies that at the first level, routes serving more satellites are preferred to routes serving only one satellite.

This means that, the first level solution can appear completely different with respect to the standard case, but does not have any effect on the satellite usage, and consequently on the second level routing. Instead, in S5 the distribution is quite uniform among satellites. This behavior coincides on what we would expect. In fact, because of the high cost of central arcs, the minimization of total cost would avoid to use them, as much as it possible. For doing that each customer is assigned to a satellite located in the same part of the city from which it can be reached without crossing the center. This kind of solution can be used with profit in many real applications, in which the best solution in terms of distances, generally, does not correspond to the most advantageous one.

STANDARD	CUST	SAT			SAT USAGE		
Instance50-s5-37.dal	RANDOM	RANDOM	15.60%	27.80%	17.20%	22.40%	17.00%
Instance50-s5-39.dal	RANDOM	SLICED	28.50%	20.40%	17.40%	16.60%	17.10%
Instance50-s5-41.dal	RANDOM	FORBIDDEN	7.80%	17.30%	33.00%	17.60%	24.30%
Instance50-s5-43.dal	CENTROIDS	RANDOM	9.60%	34.10%	12.90%	29.20%	14.20%
Instance50-s5-45.dal	CENTROIDS	SLICED	32.80%	14.30%	16.50%	19.90%	16.50%
Instance50-s5-47.dal	CENTROIDS	FORBIDDEN	12.10%	26.40%	33.80%	15.80%	11.90%
Instance50-s5-49.dal	QUADRANTS	RANDOM	12.40%	35.10%	27.40%	14.90%	10.20%
Instance50-s5-51.dal	QUADRANTS	SLICED	17.60%	22.30%	15.90%	16.80%	27.40%
Instance50-s5-53.dal	QUADRANTS	FORBIDDEN	13.60%	13.10%	39.60%	17.30%	16.40%

S1	CUST	SAT			SAT USAGE		
Instance50-s5-37.dal	RANDOM	RANDOM	15.60%	30.60%	17.20%	19.00%	17.60%
Instance50-s5-39.dal	RANDOM	SLICED	21.90%	23.80%	18.80%	15.50%	20.00%
Instance50-s5-41.dal	RANDOM	FORBIDDEN	7.80%	17.30%	33.00%	17.60%	24.30%
Instance50-s5-43.dal	CENTROIDS	RANDOM	9.60%	34.10%	12.90%	29.20%	14.20%
Instance50-s5-45.dal	CENTROIDS	SLICED	35.30%	13.80%	16.60%	14.40%	19.90%
Instance50-s5-47.dal	CENTROIDS	FORBIDDEN	12.10%	26.40%	33.80%	15.80%	11.90%
Instance50-s5-49.dal	QUADRANTS	RANDOM	12.40%	35.10%	27.40%	14.90%	10.20%
Instance50-s5-51.dal	QUADRANTS	SLICED	17.60%	22.30%	15.90%	16.80%	27.40%
Instance50-s5-53.dal	QUADRANTS	FORBIDDEN	13.60%	13.10%	39.60%	17.30%	16.40%

S2	CUST	SAT			SAT USAGE		
Instance50-s5-37.dal	RANDOM	RANDOM	15.60%	30.60%	17.20%	19.00%	17.60%
Instance50-s5-39.dal	RANDOM	SLICED	21.90%	23.80%	18.80%	15.50%	20.00%
Instance50-s5-41.dal	RANDOM	FORBIDDEN	7.80%	17.30%	33.00%	17.60%	24.30%
Instance50-s5-43.dal	CENTROIDS	RANDOM	9.60%	34.10%	12.90%	29.20%	14.20%
Instance50-s5-45.dal	CENTROIDS	SLICED	35.30%	13.80%	16.60%	14.40%	19.90%
Instance50-s5-47.dal	CENTROIDS	FORBIDDEN	12.10%	26.40%	33.80%	15.80%	11.90%
Instance50-s5-49.dal	QUADRANTS	RANDOM	12.40%	35.10%	27.40%	14.90%	10.20%
Instance50-s5-51.dal	QUADRANTS	SLICED	17.60%	22.30%	15.90%	16.80%	27.40%
Instance50-s5-53.dal	QUADRANTS	FORBIDDEN	13.60%	13.10%	39.60%	17.30%	16.40%

S3	CUST	SAT			SAT USAGE		
Instance50-s5-37.dat	RANDOM	RANDOM	15.60%	30.60%	17.20%	19.00%	17.60%
Instance50-s5-39.dat	RANDOM	SLICED	21.90%	23.80%	18.80%	15.50%	20.00%
Instance50-s5-41.dat	RANDOM	FORBIDDEN	7.80%	17.30%	33.00%	17.60%	24.30%
Instance50-s5-43.dat	CENTROIDS	RANDOM	9.60%	34.10%	12.90%	29.20%	14.20%
Instance50-s5-45.dat	CENTROIDS	SLICED	35.30%	13.80%	16.60%	14.40%	19.90%
Instance50-s5-47.dat	CENTROIDS	FORBIDDEN	12.10%	26.40%	33.80%	15.80%	11.90%
Instance50-s5-49.dat	QUADRANTS	RANDOM	12.40%	35.10%	27.40%	14.90%	10.20%
Instance50-s5-51.dat	QUADRANTS	SLICED	17.60%	22.30%	15.90%	16.80%	27.40%
Instance50-s5-53.dat	QUADRANTS	FORBIDDEN	13.60%	13.10%	39.60%	17.30%	16.40%

Table 2. Satellite usage for scenarios S1, S2 and S3

S4	CUST	SAT			SAT USAGE		
Instance50-s5-37.dat	RANDOM	RANDOM	15.60%	30.60%	17.20%	19.00%	17.60%
Instance50-s5-39.dat	RANDOM	SLICED	21.90%	23.80%	18.80%	15.50%	20.00%
Instance50-s5-41.dat	RANDOM	FORBIDDEN	7.80%	17.30%	33.00%	17.60%	24.30%
Instance50-s5-43.dat	CENTROIDS	RANDOM	9.60%	34.10%	12.90%	29.20%	14.20%
Instance50-s5-45.dat	CENTROIDS	SLICED	35.30%	13.80%	16.60%	14.40%	19.90%
Instance50-s5-47.dat	CENTROIDS	FORBIDDEN	12.10%	26.40%	33.80%	15.80%	11.90%
Instance50-s5-49.dat	QUADRANTS	RANDOM	12.40%	35.10%	27.40%	14.90%	10.20%
Instance50-s5-51.dat	QUADRANTS	SLICED	17.60%	22.30%	15.90%	16.80%	27.40%
Instance50-s5-53.dat	QUADRANTS	FORBIDDEN	13.60%	13.10%	39.60%	17.30%	16.40%

S5	CUST	SAT			SAT USAGE		
Instance50-s5-37.dat	RANDOM	RANDOM	12.80%	23.20%	19.60%	21.50%	22.90%
Instance50-s5-39.dat	RANDOM	SLICED	21.90%	23.80%	18.00%	16.30%	20.00%
Instance50-s5-41.dat	RANDOM	FORBIDDEN	17.60%	24.00%	20.20%	19.80%	18.40%
Instance50-s5-43.dat	CENTROIDS	RANDOM	19.70%	17.50%	22.90%	23.60%	16.30%
Instance50-s5-45.dat	CENTROIDS	SLICED	24.90%	22.60%	13.10%	14.70%	24.70%
Instance50-s5-47.dat	CENTROIDS	FORBIDDEN	26.00%	16.00%	18.90%	22.30%	16.80%
Instance50-s5-49.dat	QUADRANTS	RANDOM	19.90%	22.20%	17.70%	23.20%	17.00%
Instance50-s5-51.dat	QUADRANTS	SLICED	22.90%	19.40%	16.70%	17.60%	23.40%
Instance50-s5-53.dat	QUADRANTS	FORBIDDEN	18.00%	22.00%	24.80%	17.10%	18.10%

Table 3. Satellite usage for scenarios S4 and S5

ANALYSIS OF DIFFERENT TRAFFIC CONDITIONS

In this section we present three different temporal scenarios, each one representing a different part of the day, with the related traffic conditions. The first one, S6, represents a typical early morning situation, in which incoming arcs are heavy congested, outgoing arcs are subjected to normal traffic conditions while downtown arcs are lightly congested. The second one, S7 represents a late afternoon situation, in which outgoing arcs are heavy congested, incoming arcs are subjected to normal traffic conditions while downtown arcs are heavy congested. Finally, the last scenario S8 represents an early afternoon situation, where downtown arcs are

congested while the other arcs have a normal traffic condition. All the scenarios represent situations related to a standard working day, while during weekends, holidays, or summer periods, traffic conditions may be different. For heavy congested arcs we consider a travel time 3 times greater than in normal conditions. For congested arcs the travel time is doubled and for light congested arcs it is 50% higher.

In Table 4 we report the results obtained on scenarios S6, S7 and S8 where the two columns S7-GAIN and S8-GAIN report, respectively, the percentage cost reduction obtainable performing the delivery in the late afternoon (S7) and in the early afternoon (S8) with respect to doing it in the early morning (S6). As one can observe, there is a very strong cost reduction in both cases (between 40% and 46% for S7 and between 50% and 53% for S8), but the highest reduction is obtained by performing the delivery operations in the early afternoon. Nevertheless, this strategy cannot be actuated in any situation because in several real applications (like bread and fresh pastries delivery, newspapers delivery etc.) goods must be delivered in the early morning. For a global reduction of costs, delivery operations not subjected to this particular constraint could be performed in the afternoon, reducing the traffic congestion in the early morning, when the requested activities must be performed at lower costs.

For what concerns the satellites usage, for S6 we can notice the same demand distributions among satellites as in the STANDARD case, while for S7 and S8 the distributions are the same as the one obtained for S5. More in details, in S6 the first level routes are the same as in case STANDARD, but sometimes they are covered in the opposite way in order to reach for first the satellite nearest to the depot letting the longest arc for the way back while in that direction the traffic congestion is lower. In S7 and S8 downtown arc costs are very high and for that reason the best strategy is to try avoid to use them, as much as possible. For doing that each customer is assigned to a satellite located in the same part of the city from which it can be reached without crossing the center, as it happens for S5. In Table 4 we report a comparison between the Two-Echelon (2EVRP) and the Single-Echelon distribution approach (VRP). The VRP is realized performing the delivery without passing through the satellites, using a fleet of vehicles equal to the vehicles used in the second level of the 2EVRP. If we compare the 2EVRP with the standard VRP we can notice that our approach is always strongly preferable because it allows, for all the scenarios, an average cost reduction of 55% with respect to the standard VRP method. The best gain is obtained on S7 and S6 where the depot to city connection costs are higher. In fact, in the standard VRP approach vehicles are obliged to come back to the depot at the end of each route, which implies a larger use of incoming (S6) and outgoing (S7) arcs, which yields very high costs. Anyway, even in S8, where higher costs are related to central arcs, the gain of our approach is still large (around 43%). It is correct to remind that we are not considering satellite opening and management costs which would increase the 2EVRP global costs.

S5				S7				S8		
VRP	2EVRP	GAIN		VRP	2EVRP	GAIN		VRP	2EVRP	GAIN
7500.11	3313.00	55.83%		5700.01	1924.24	66.24%		2789.98	1598.00	42.72%
7500.11	3172.72	57.70%		5700.01	1734.00	69.58%		2789.98	1518.98	45.56%
7500.11	3541.00	52.79%		5700.01	2029.92	64.39%		2789.98	1702.00	39.00%
7444.13	3198.91	57.03%		5544.29	1897.97	65.77%		2777.56	1595.96	42.54%
7444.13	3027.27	59.33%		5544.29	1774.10	68.00%		2777.56	1506.10	45.78%
7444.13	3497.90	53.01%		5544.29	2071.71	62.63%		2777.56	1560.00	43.84%
7490.09	3115.15	58.41%		5318.98	1752.25	67.06%		2687.39	1519.90	43.44%
7490.09	3056.65	59.19%		5318.98	1649.99	68.98%		2687.39	1429.00	46.83%
7490.09	3330.92	55.53%		5318.98	1792.00	66.31%		2687.39	1582.22	41.12%

Table 4. Comparison with the VRP approach for scenarios S6, S7 and S8

CONCLUSION

The scope of the paper is to analyze how different travel costs may affect the satellite location in the 2E-VRP and if this approach is preferable to the single-echelon one. A detailed analysis of computational results shows how the satellite usage is not affected by the increasing of incoming and/or outgoing arc costs, while, when the downtown arc costs increase, the satellite usage strongly change, assuming a configuration with a uniform demand distribution among satellites. Moreover, a cost reduction could be obtained by performing the delivery operations in the afternoon, reducing the traffic congestion in the early morning, when the deliveries which are strictly requested to be performed in this period could be made at lower costs.

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