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# A procedure for optimizing hazardous materials transportation including road infrastructures' characteristics and door-to-door attempted deliveries

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**Abstract**

This study deals with downstream logistics of Liquefied Petroleum Gas (LPG) by tank trucks both at regional and urban level. The distribution problem is formulated as a capacitated Vehicle Routing Problem (VRP) with time windows. Its solution is based on a two steps procedure with the aim of maximizing the revenue of the logistic operator: 1) in the first step, the problem is solved at suburban level, where each delivery point represents a municipality in the study area. The employed objective function of the VRP has been conceived as to integrate the usual operating costs with aspects related to infrastructure characteristics of the used paths; 2) in the second step, door to door deliveries at urban level are attempted, taking into account the operating costs and the last delivery time for each potential client.
The method has been applied in a real case study based in the city of Perugia, Italy. Sensitivity analysis considering different values for the parameters regulating the relative weights of the objective function components has been performed.
Results show that the potential revenues for the operator can be doubled through the proposed optimization procedure. Moreover, explicitly taking into account that not all roads are suitable for vehicles transporting hazardous materials can increase the security of the distribution process, resulting in a service cost increase of just +1.4% with respect to extant conditions.



*Keywords:* VRP; hazmat transportation; downstream logistics; fuel distribution

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## 1. Introduction

In the gas and oil sector, logistics provides and coordinates the necessary infrastructure for stockpiling, inventory management and transport of goods, from storage to the consumer, in a timely and prescribed fashion, ensuring efficiency and achieving the lowest possible cost.

This study deals with downstream logistics of Liquefied Petroleum Gas (LPG) by tank trucks both at regional and urban level. This approach considers therefore hazardous material (hazmat) transportation, which is subject to particular restrictions, calling for special applications of quantitative modelling (see e.g. Batta and Kwon, 2013, for a general overview).

Specific literature focuses on this interesting problem, highlighting the complexity of the fuel distribution sector. In fact, several works in literature have investigated a large variety of operational constraints and algorithmic approaches (Cornillier et al, 2008-2009, Vidal et al., 2012, Triki, 2013). Usually, heuristic methods are adopted due to the large size of the real instances which fuel companies have to typically deal with (Carotenuto et al, 2018).

The decision process follows the minimization of the total length traveled by tank trucks, total time spent or trough generalized cost functions. A so far largely disregarded feature to be included within the decision process of fuel distribution concerns road infrastructure characteristics (Cuneo et al., 2018), since not all roads are suitable for heavy vehicles transporting hazardous materials.

In this paper, the distribution problem is formulated as a capacitated Vehicle Routing Problem (VRP) with time windows. Its solution is based on a two steps procedure with the aim of maximizing the revenue of the logistic operator:

1. in the first step, the problem is solved at suburban level, where each delivery point represents a municipality of the study area. In this first step, the objective function of the VRP has been conceived as to integrate the usual operating costs with aspects related to road infrastructures characteristics;
2. in the second step, the door to door deliveries at urban level are attempted, taking into account the operating costs and the last delivery time of each potential customer. Thus, the delivery points identified as places of potential sale during the first step represent the starting locations for the application of the second step.

The contributions of the paper are twofold: i) to increase the security of hazmat transport taking into account the roads features and ii) to integrate the “attempted deliveries” in the planning phase. Considering a composite measure in the first step of the optimization leads to an inherent multi-objective problem, seeking to establish a tradeoff between costs, distance travelled, or a combination of them (similar to Alexiou and Katsavounis, 2015). However, the concept of “attempted deliveries”, i.e. door to door salesmanship concerning habitual customers, investigating whether they might need a refill of LPG, is not considered in standard distribution approaches from literature. This could be considered as a “real time” strategy devised in order to increase the revenue from LPG sales.

The procedure has been applied for the real case of the “Univergas Italia Srl” fuel distribution company, specifically considering the distribution of LPG in the territory of the Province of Perugia. Since Univergas requires managing also the commercial segment of “attempted deliveries”, the purpose of this analysis is to respond to a core need of the company.

The outline of the remainder of this paper is as follows. In Section 2 we present the proposed methodology. Section 3 summarizes the results for the Perugia case study, including a sensitivity analysis. Finally, Section 4 concludes the paper and discusses avenues for future works.

## 2. Methodology

The steps of the developed method are as follows.

In the initialization phase, the road network is replicated on a GIS platform. For each link, several features about road characteristics are reported, specifically slope, the straight-line gradient, the vertical and horizontal curvature, the vertical and horizontal radius, together with their length. The data were provided by the database on the road network of the Province of Perugia (Italy). For each node, data related to the Univergas service are reported, such as demand data (quantity of LPG and price) based on previous discharges. Finally, information on fleet characteristics are available (such as capacity of the tank-truck and number of trucks).

In the first step, given the collected data and the network, a minimum path algorithm is applied between each origin-destination nodes according to a parametric distance containing also information on the infrastructural features of the paths. The minimum paths are then taken as input to solve a Capacitated Vehicle Routing Problem (VRP) for the distribution of LPG in the whole province.

Finally, in the second step of the methodology, a second level VRP is solved to promote door to door deliveries at local (urban) level.

The entire methodology has been subject to a validation phase, through a sensitivity analysis.

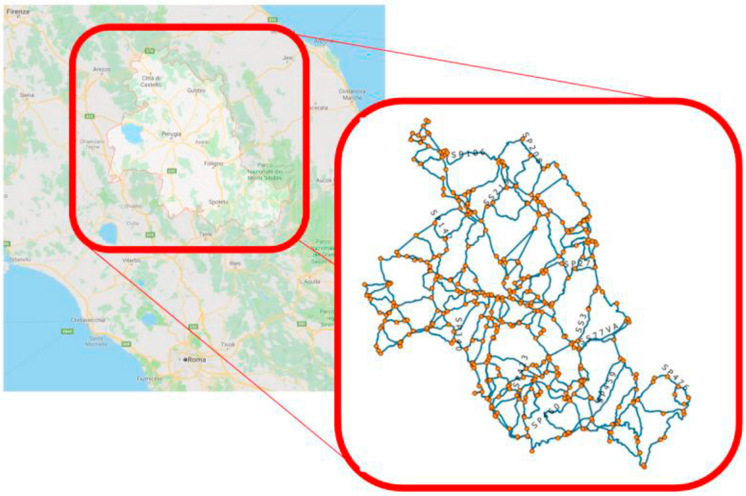

Fig. 1. Network graph of the province of Perugia.

## *2.1. First step: Route optimization including geometric features of the road network*

The road network graph for the province of Perugia consists of 546 links and 394 nodes (including one depot and 57 potential delivery points for LPG demand). A parametric distance between each couple of nodes (*i,j*) is computed as:

$$d_{ij,geom} = d_{ij} + d_{P,ij} + d_{A,ij} \tag{1}$$

where:

$d_{ij}$ = physical length of the link between i and j;

$d_{P,ij}$ = "planimetric" distance component, computed as:

$$d_{P,ij} = \varepsilon_1 \left(\alpha d_{straight} + \beta d_{curve}\right) \tag{2}$$

with:

$d_{straight}$ = length of the straight part of the link;

$d_{curve}$ = length of the curve of the link;

$d_{A,ij}$ = "altimetric" distance component, computed as:

$$d_{A,ij} = \varepsilon_2 \left(\gamma d_{straight\_grad} + \delta d_{vertical\_curve}\right) \tag{3}$$

with:

$d_{straight\_grad}$ = length of the straight-line gradient of the link;

$d_{vertical\_curve}$ = length of the vertical curve of the link;

thus obtaining a symmetric 394x394 adjacency cost matrix; $\varepsilon_1$ and $\varepsilon_2$ represent respectively the weights of the planimetric and of the altimetric components, with sum equal to 1. The coefficients α, β, γ, δ are the weights of the parametric distances; $\alpha$ is set equal to 1, since the length of the straight part of the link does not contribute to any risk factor for tank-trucks.

β is the weight for $d_{curve}$, its value ranging between [1;2] and computed as follows:

$$\beta = \frac{Rm - B}{A - B} + 1 \qquad \text{with } Rm = \text{minimum horizontal radius [m] of the link} \tag{4}$$

γ is the weight for $d_{straight\_grad}$, its value ranging between [1;2] and computed as follows:

$$\gamma = \frac{\Delta Im - A}{B - A} + 1 \qquad \text{with } \Delta Im = \text{maximum slope [\%] of the link} \tag{5}$$

δ is the weight for $d_{vertical\_curve}$, its value ranging between [1;2] and computed as follows:

$$\delta = \frac{Rvm - B}{A - B} + 1 \qquad \text{with } Rvm = \text{minimum vertical radius [m] of the link} \tag{6}$$

A and B respectively represent the minimum and maximum values of the geometric components analyzed for the whole network of the province of Perugia.

A shortest-path algorithm is applied between each couple of centroids (origin-destination points), employing the 394x394 matrix of parametric distances. After the identification of the shortest-path tree, the 58x58 distance matrix was produced. This is the input to solve a Capacitated Vehicle Routing Problem (VRP) for the distribution of LPG in the whole province, adopting the VRP Spreadsheet Solver by Gunes E. (2017) and based on an adaptive large neighborhood search algorithm. VRP is widely applied to distribution problems, exhibiting significant cost savings (Hasle and Kloster, 2007). For in-depth reviews of VRP, the reader is referred to Flamini et al. (2018) and Flamini et al. (2011). The Objective Function (O.F.) defined for the VRP is:

$$\sum_{i\in Vc}\sum_{k\in K}\tilde{p}_i\, y_i^k - \sum_{(i,j)\in A}\sum_{k\in K}\hat{c}_{ij}\, x_{ij}^k - \pi\sum_{i\in V}\hat{v}_i \tag{7}$$

It maximizes the potential profit minus the operational cost (including fixed costs of the vehicle), minus a penalty function accounting for violations of delivery time windows.

When solving (7) at the regional level, each term of the O.F. is specified as follows:

1. $\tilde{p}_i$ is potential profit related to LPG deliveries:

$$\tilde{p}_i = \tilde{q}_{il} * C_{uGPL} * L_{Pro} \tag{8}$$

where:

- $\tilde{q}_{il}$ the liters to be delivered;
- $C_{uGPL}$ the unit cost (per liter) of LPG excluding VAT;
- $L_P$ is a coefficient, computed as:

$$L_P = \mu_i * \theta_i \tag{9}$$

with:

- $\mu_i$ quantifies the unloading potentiality of each municipality *i* with respect to the others of the region; $1 < \mu_i \leq 2$ ; computed as:

$$\mu_i = \frac{N°\,tank - N°tank\_min}{N°tank\_max - N°tank\_min} + 1 \tag{10}$$

- $\theta_i$ represents the probability of the delivery for the municipality *i;* $0 < \theta_i \leq 1$*;* computed as: $\theta_i = \frac{2^{N°tank} - 1}{2^{N°tank}}$ (11)

2. the second term of (7) is the transport cost of moving on path *k*: it is based on the shortest paths computed adopting the parametric distances and on the unit transport cost $C_{uT}$ [€/km] as derived by Resolution 18/OS/CGA (2012):

$$\sum_{(i,j)\in A}\sum_{k\in K}\hat{c}_{ij}\, x_{ij}^k = g\left(d_{ij,geom}; C_{uT}\right) \tag{12}$$

3. $\hat{v}_i$ represents the number of times the time windows are violated and it is indirectly function of the shortest paths based on the parametric distances and of the average speed $\bar{v}_{ij}$ on the link:

$$\hat{v}_i \ (t_{ij}(d_{ij,geom} \ ; \ \bar{v}_{ij})) \tag{13}$$

*2.2. Second step: Door to door deliveries*

In the second step of the methodology, a second level VRP is solved to promote the door to door deliveries at the local (urban) level. This implies that deliveries are not planned off-line, and instead they are attempted in real time for each municipality. The VRP is in this case solved to find the optimal routes within each municipality. The O.F. adopted for this problem is essentially that of equation (7), with different coefficients with respect to those employed in (8-11), derived instead as follows:

1. $\tilde{p}_i$ is the potential profit due to the LPG door to door deliveries:

$$\tilde{p}_{iL} = \tilde{q}_{ilL} * C_{uGPL} * L_{Loc} \tag{14}$$

where:

- $\tilde{q}_{il}$ the liters to be delivered;
- $C_{uGPL}$ the unit cost (per liter) of LPG excluding VAT;
- $L_{Loc}$ is a coefficient, computed as:

$$L_{Loc} = \sigma_{iL} * \tau_{iL} \tag{15}$$

with:

- $\sigma_{iL}$ takes into account the price proposed by the Company, according to the price of the last delivery; $0 < \sigma_{iL} \leq 1$ , computed as: $\sigma_{iL} = 1 - \frac{€\text{proposed} - €\,\text{lastdelivery}}{€\min \textit{last delivery} - €\max \textit{last delivery}}$ (16)
- $\tau_{iL}$ takes into account the time from the last delivery; $0 < \tau_{iL} \leq 1$, computed as: $\tau_{iL} = 1 - \frac{\Delta\text{time}_{today} - max\Delta\text{time}}{min\Delta\text{time} \quad - max\Delta\text{time}}$ (17)

2. the second term of (7) is the transport cost of moving on the path *k*; however, it is a function of the shortest paths based on travel times and not on the shortest paths based on the parametric distances;

3. $\hat{v}_i$ represents the number of times time windows are violated, and it is a function of travel times:

$$\hat{v}_i \ (t_{ij}(d_{ij}|_{\min \textit{travel time}})) \tag{18}$$

## 3. Results

The output of the whole procedure identifies the sequence of nodes to be visited with their respective time windows. In Figure 2 an example of a generated route by the first level and the related door to door service provided for the two specific municipalities of Foligno and Spoleto is reported. The results refer to a typical weekday of February; the maximized potential profit is equal to about 3,200 euros against a net profit of 1,700 euros without attempted door to door deliveries. This implies that, for this specific scenario, the potential revenues for the operator can be doubled if explicit planning of attempted door to door deliveries is included in the optimization procedure.

*3.1. Sensitivity analysis*

The results of the procedure have been analyzed by changing the weights employed in the computation of the parametric distances.

Starting from the ε weights reported in (2) and (3), if we increase $\varepsilon_1$ of the planimetric component, in compliance with the condition $\varepsilon_1 + \varepsilon_2 = 1$, there is a constant increase in the length of the routes traveled by the tank trucks. The performed analysis shows a strong change of this cost increase (about 8 km) when moving from $\varepsilon_1 = 0.6$ to $\varepsilon_1 = 0.7$, which corresponds to a significant reduction of the expected profits. Thus, the value $\varepsilon_1 = 0.6$ can be seen as the threshold for this specific case of study, although in general this threshold will clearly depend on the geometric characteristics of the network and the GPL demand pattern. The adoption of $\varepsilon_1 = 0.6$ and $\varepsilon_2 = 0.4$ in the final application (Fig. 2) follows these considerations.

The total kilometers of the network (computed as the sum of the distances inside the shortest paths matrix) yield a slightly more than linear trend in terms of impact (Fig.3, c).

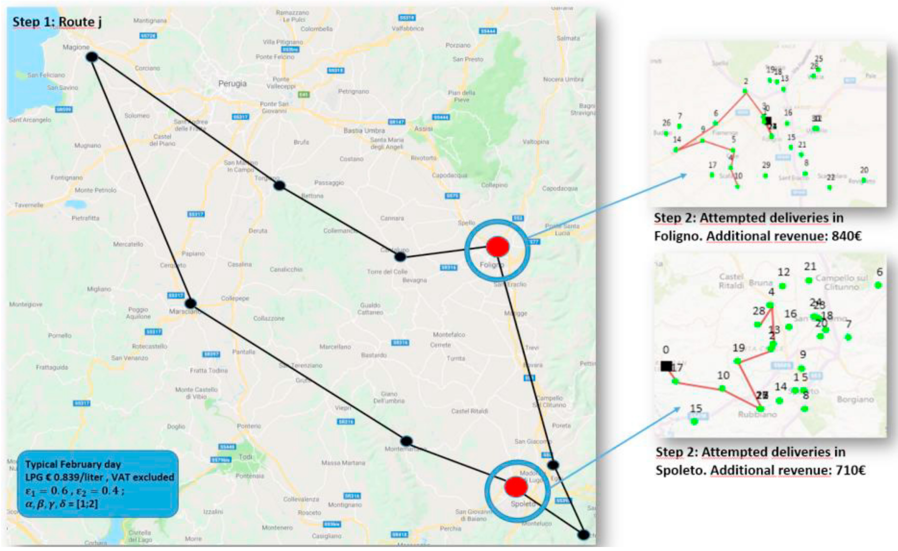


Fig. 2. Output of the procedure both at provincial level and with the “attempted deliveries” in the cities of Foligno and Spoleto.

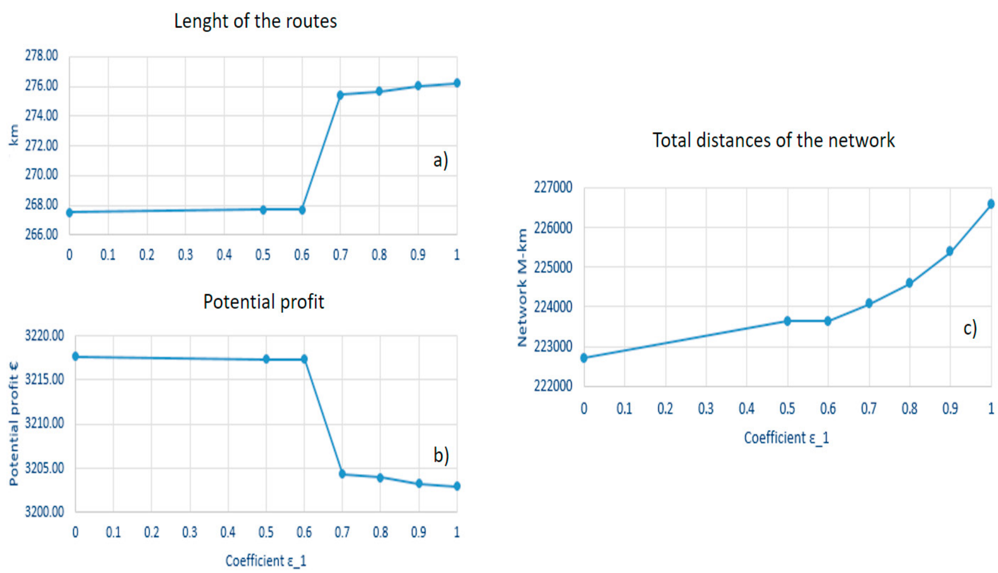


Fig. 3.; (a) Distances developed by the operator; (b) Potential profit; (c) Overall development of network’s distances

Perturbation of the weights β, γ and δ in equations (2) and (3), a higher elasticity of the results in terms of length of the routes for the operator can be observed in connection to the vertical and the horizontal radius (Fig.4, a). The orange line in Fig.4 is the limit beyond which the conditions of the analyzed day are no longer respected (i.e. the maximum time limit for the deliveries is 6:00 pm; the mandatory deliveries are supplied; the attempted door to door delivery is not canceled).

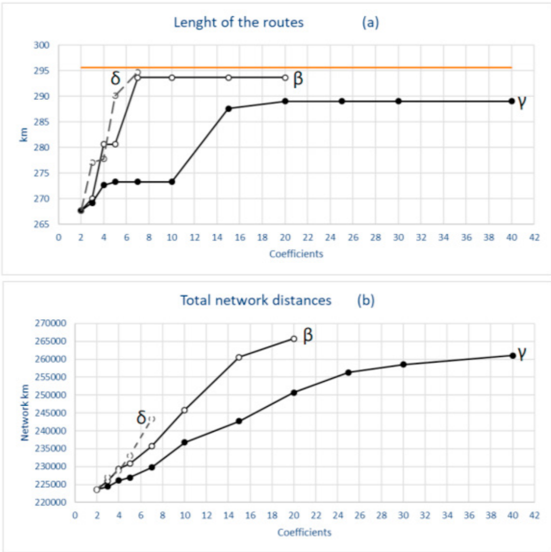


Fig. 4. (a) Distances developed by the operator; (b) Overall development of network's distances.

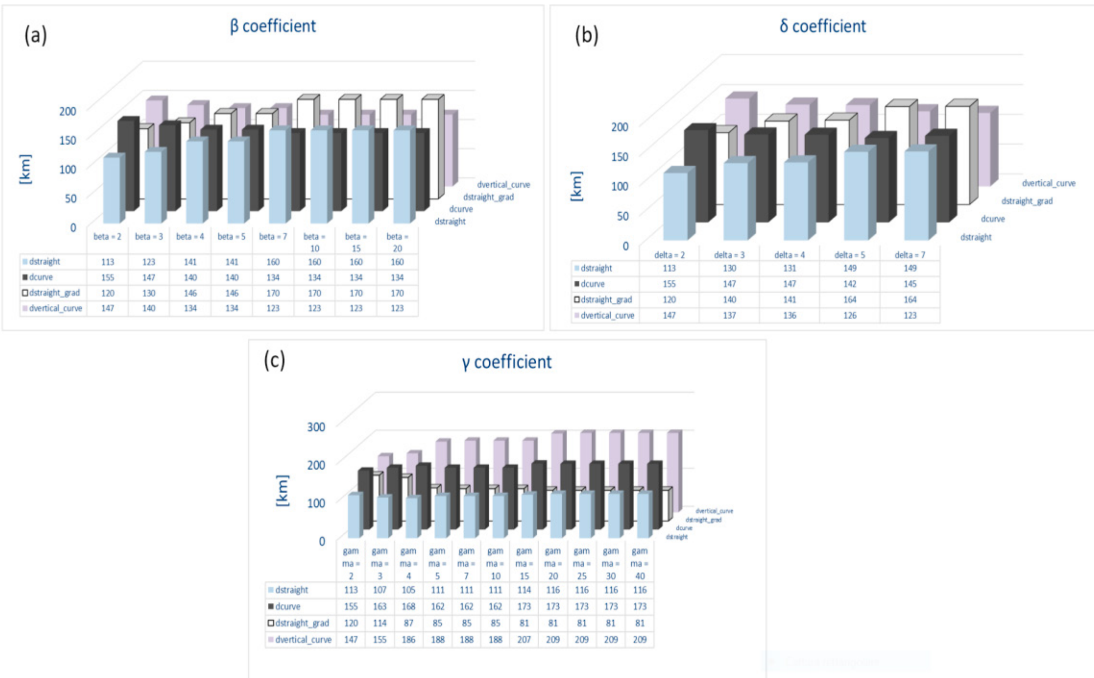


Fig. 5. (a) Change in "Route length components" for different β values (linked to the horizontal curve); (b) Change in "Route length components" for different δ values (linked to the vertical curve); (c) Change in "Route length components" for different γ values (linked to the slop).

As can be seen in both Fig. 4 and Fig.5, the weights β, γ and δ are tested also for values higher than 2. In the Univergas starting application we set the weights to values lower than 2 in order not to introduce imbalance in the altimetric and the planimetric distance components of equation (1) with respect to the geometric distance $d_{ij}$. However, higher values can be given in order to increase the impact of the related component.

Specifically, in case of extreme attention to safety conditions, thus increasing the weights β,γ and δ, the impacts on the reduction of the potential profit for the operator is at most -1.36% considering on the horizontal curve, -1.11% considering on the slope, - 1.41% considering on vertical curve.

## 4. Conclusions

We have developed a methodology that performs route optimization in downstream logistics of LPG taking into account the infrastructure characteristics of the road network together with attempted door to door deliveries. It works both at a coarse spatial level (regional level) and at local level (urban level), maximizing the potential profits.

The results of a typical weekday show a potential profit of about 3,200€ compared to a value of 1,700€ obtained disregarding the opportunity of performing attempted door to door deliveries.

The adoption of weights for the geometric components inside the parametric distance computation leads to a maximum incidence on the potential profit of -1.36% for the horizontal curve, -1.11% for the slope and - 1.41% for the vertical curve. However, these reductions need to be evaluated considering the added value of an increment in safety and security for hazmat deliveries.

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