EVALUATING VEHICLE ROUTING PROBLEMS WITH SUSTAINABILITY COSTS

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Abstract: In this paper, we study the road freight transportation activities, which are significant sources of air pollution, noise and greenhouse gas emissions, with the former known to have harmful effects on human health and the latter, responsible for global warming. Specifically, an extension of the classical Capacitated Vehicle Routing Problem is presented, including realistic assumptions (Time Windows, Backhauls and Heterogeneous Fleet with different vehicles and fuel types). The decisions are aimed at the selection of vehicle and fuel types, the scheduling of deliveries and pick-up processes and the consolidation of freight flows. The classical objective functions of minimizing the total travel distance or the internal costs (driver, fuel or maintenance) are extended to other sustainable measures: the amount of air pollution and greenhouse gas emissions, the energy consumption and their costs. A mathematical model is described and an illustrative example is performed.

1 INTRODUCTION

Environmental issues can impact on numerous logistical decisions throughout the supply chain such as location, sourcing of raw material, modal selection, and transport planning, among others. Green logistics extends the traditional definition of logistics by explicitly considering other external factors associated mainly with climate change, air pollution, noise, vibration and accidents.

The logistical activities comprise freight transport, storage, inventory management, materials handling and all the related information processing. In this paper, we study the road freight transportation activities, which are significant sources of air pollution, noise and greenhouse gas emissions, with the former known to have harmful effects on human health and the latter, responsible for global warming.

An eco-efficiency model of the classical Vehicle Routing Problem with some realistic assumptions (Heterogeneous Fleet, Time Windows and Backhauls) is presented with a broader objective function that accounts not just for the internal costs (driver, fuel, maintenance,…), but also for external costs (greenhouse emissions, air pollution, noise,…). With this new mixed-integer linear programming (MILP) model, transportation companies can have positive environmental effects by making some operational changes in their logistics system, selecting the most appropriate vehicles, determining the routes and schedules to satisfy the demands of the customers, reducing externalities and achieving a more sustainable balance between economic, environmental and social objectives.

This paper is structured as follows. In the next section, a review of existing literature in VRP is presented. The different externalities are analyzed and their costs are internalized in Section 3. Section 4 provides a formal description of the problem and the mathematical model. Section 5 illustrates the proposed approach on a four-node example. An analysis of the illustrative example is presented in Section 6. Finally, conclusions and references are presented.

2 LITERATURE REVIEW

The Vehicle Routing Problem (VRP) is a well known problem in operational research where the optimal routes of delivery or collection from one or several depots to a number of customers are found, while satisfying some constraints and minimizing the total distance travelled. Huge research efforts have been devoted to studying the VRP since 1959

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and thousands of papers have been written on several VRP variants. We refer to the survey by (Cordeau et al. 2007) for a recent coverage of the state-of-the-art on models and solution algorithms.

When demand of all customers exceeds the vehicle capacity, two or more vehicles are needed. This implies that in the Capacitated Vehicle Routing Problem (CVRP) multiple Hamiltonian cycles have to be found such that each Hamiltonian cycle is not exceeding the vehicle capacity.

The Vehicle Routing Problem with Time Windows (VRPTW) occurs when customers require pick-up or delivery within pre-specified service times. The VRPTW has been the subject of intensive research efforts for both heuristic and exact optimization approaches. An overview of the early published papers is given by (Solomon, 1987).

The Heterogeneous Fleet Vehicle Routing Problem (HF-VRP) drops the assumption that the vehicle fleet has identical characteristics for each vehicle. It should be clear that in some applications a mix of vehicles with different capacities or properties can be more useful than the use of a single vehicle type. An interesting question discussed in (Salhi & Rand, 1993) is what the optimal composition of the vehicle fleet should be.

The Vehicle Routing Problem with Backhauls (VRPB) considers that besides the deliveries to a set of customers (linehaul customers), a second set of customers requires a pick up (backhaul customers), that is, all deliveries must be made on each route before any pickups can be made. This arises from the fact that the vehicles are rear-loaded.

This paper deals with the Vehicle Routing Problem with Heterogeneous Fleet, Time Windows and Backhauls (HF-VRPTW-B). This problem is extremely frequent in the grocery industry, where customer set is partitioned into two subsets (i) supermarkets are the linehaul customers, each requiring a given quantity of product to be delivered; and (ii) grocery suppliers are the backhaul customers, in which a given quantity of inbound product must be picked up (Toth & Vigo, 2002).

The classical objective function in VRP is minimizing the total distance travelled by all the vehicles of the fleet or minimizing the overall travel cost, usually a linear function of distance. Some authors (Sniezek & Bodin, 2002) argue that only considering total travel time or total travel distance in the objective function is not enough in evaluating VRP solutions, especially for non-homogeneous fleets. Instead, they determine a Measure of Goodness, which is a weighted linear combination of many factors such as capital cost of a vehicle, salary cost of the driver, overtime cost and mileage cost. These costs are considered as internal or economic costs for transportation companies.

Internalization of external cost of transport has been an important issue for transport research and policy development for many years in Europe and worldwide. Some authors (Bickel et al. 2006) focus their research on evaluating the external effects of transport to internalize them through taxation. As a result, decisions such as the selection of vehicle types, the scheduling of deliveries, consolidation of freight flows and selection of type of fuel, considering internal and external costs can help to reduce the environmental impact without losing competitiveness in transport companies.

In recent years, some authors present integrated routing with time windows and emission models for freight vehicles (Maden et al. 2010; Bektas & Laporte, 2011). They take into account the amount of CO_2 emissions and fuel consumption, but they don’t consider heterogeneous fleet and other externalities such as atmospheric pollutants, noise or accidents.

3 EXTERNALITY EVALUATION

In the last decade interest in environment preservation is increasing and environmental aspects play an important role in strategic and operational policies. Therefore, environmental targets are to be added to economical targets, to find the right balance between these two dimensions (Dyckhoff et al. 2004).

In this paper, we focus our attention on external costs associated with: greenhouse emissions, atmospheric pollutant emissions, noise emissions and accidents. These four components reflect 88% of the total average external cost freight in the European Union, excluding congestion costs (INFRAS/IWW, 2004). The evaluation of each component of the external costs applied to the Spanish transport setting is based on the European study (INFRAS et al, 2008).

Climate change or global warming impacts of transport are mainly caused by emissions of the greenhouse gases: carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). The main cost drivers for marginal climate cost of transport are the fuel consumption and carbon content of the fuel. The recommended value for the external costs of climate change for year 2010, expressed as a central estimate is 25€/ton.CO_2. The total well-to-wheel CO_2 emissions per unit of fuel, also called emission factor, is estimated in 2.67 kg of CO_2 per litre of diesel.

Air pollution costs are caused by the emission of air pollutants such as particulate matter (PM), NO_x and non-methane volatile organic compounds (NMVOC). For internalization purposes the estimated external costs of each pollutant emissions can be obtained by multiplying the grams of the pollutant per kilometer travelled with the external costs per gram of pollutant emitted. The recommended air pollution costs for each pollutant in Spain (emissions 2010, in €2000/ton of pollutant) are: NO_x=2600; NMVOC=400; $PM_{2.5}$=41200; PM_{10}=16500, using PM in outside built-up areas. The ratio €2010/€2000 is fixed to 1.323. The estimation of pollutant emissions from road transport are based on the Tier 2 methodology (EMEP/EEA, 2010). This approach considers the fuel used for different vehicle categories and technologies.

Noise costs consist of costs for annoyance and health. The recommended noise costs for Heavy-Duty Vehicles are in a range from 0.25 to 32 (in €2000/ton-km), with a mean value of 4.9.

External accident costs are those social costs of traffic accidents which are not covered by risk oriented insurance premiums. The recommended accident costs for Heavy-Duty Vehicles are in a range from 0.7 to 11.8 (in €2000/ton-km), with a mean value of 4.75.

In this paper, the routes design will employ all of these average costs and emission factors, multiplying these parameters by the respective distance travelled, load carried or fuel consumed in each route.

4 PROBLEM MODELING

The HF-VRPTW-B is defined on a graph G={N,A} with N={0,1,…,t,t+1,…,n} as a set of nodes, where node 0 represents the depot, nodes numbered 1 to t represent delivery points and nodes numbered t+1 to n represent supply points (backhauls), and A is a set of arcs defined between each pair of nodes. A set of m heterogeneous vehicles is available to deliver the desired demand of all customers from the depot node and then to pick-up the inbound products from the supply and return to the depot node. The constructing routes of each vehicle must meet the following constraints: no vehicle carries load more than its capacity, each customer and supplier is visited within its respective time window, customers are not visited after any suppliers and no vehicle exceeds the maximum allowable driving time per day.

We adopt the following notation:

- D_i load demanded by node i∈{1,…,t} and load supplied by node i∈{t+1,…,n}
- q^k capacity of vehicle k∈{1,…,m}
- $[e_i,l_i]$ earliest and latest time to begin the service at node i
- s_i^k service time in node i by vehicle k
- d_{ij} distance from node i to node j (i≠j)
- t_{ij} driving time between the nodes i and j
- T^k maximum allowable driving time for vehicle k

Our formulation of the problem uses de following decision variables:

- x_{ij}^k binary variable, equal to 1 if the vehicle k∈{1,…,m} travels from nodes i to j (i≠j)
- y_i^k starting service time at node i ∈{0,1,…,n}; y_0^k is the ending time
- f_{ij}^k load carried by the vehicle k∈{1,…,m} from nodes i to j (i≠j)

Constraints of the model are as follows:

$$\sum_{j=1}^{n} x_{0j}^k \le 1 \quad (k=1,...,m) \tag{1}$$

$$\sum_{\substack{j=0\\ j\neq i}}^{n} x_{ij}^k - \sum_{\substack{j=0\\ j\neq i}}^{n} x_{ji}^k = 0 \quad (k=1,...,m;\quad i=1,...,n) \tag{2}$$

$$\sum_{k=1}^{m}\sum_{\substack{j=0\\ j\neq i}}^{n} x_{ij}^k = 1 \quad (i=1,...,n) \tag{3}$$

$$\sum_{i=1}^{t} D_i \sum_{\substack{j=0\\ j\neq i}}^{n} x_{ij}^k \le q^k \quad (k=1,...,m) \tag{4}$$

$$\sum_{i=t+1}^{n} D_i \sum_{\substack{j=0\\ j\neq i}}^{n} x_{ij}^k \le q^k \quad (k=1,...,m) \tag{5}$$

$$\sum_{k=1}^{m}\sum_{i=t+1}^{n}\sum_{j=1}^{t} x_{ij}^k = 0 \tag{6}$$

$$\sum_{k=1}^{m}\sum_{j=t+1}^{n} x_{0j}^k = 0 \tag{7}$$

$$y_i^k + s_i^k + t_{ij} \le y_j^k + T^k(1-x_{ij}^k) \quad (i=1,...,n;\ j=0,...,n;\quad j\neq i;\quad k=1,...,m) \tag{8}$$

$$t_{0j} \le y_j^k + T^k(1-x_{0j}^k) \quad (j=1,...,n;\quad k=1,...,m) \tag{9}$$

$$e_i \le y_i^k \le l_i \quad (i=1,...,n;\quad k=1,...,m) \tag{10}$$

$$y_0^k \le T^k \quad (k=1,...,m) \tag{11}$$

$$\sum_{k=1}^{m}\sum_{\substack{j=0\\ j\neq i}}^{n} f_{ji}^k - \sum_{k=1}^{m}\sum_{\substack{j=0\\ j\neq i}}^{n} f_{ij}^k = D_i \quad (i=1,...,t) \tag{12}$$

$$\sum_{k=1}^{m}\sum_{\substack{j=0\\ j\neq i}}^{n} f_{ij}^k - \sum_{k=1}^{m}\sum_{\substack{j=0\\ j\neq i}}^{n} f_{ji}^k = D_i \quad (i=t+1,...,n) \tag{13}$$

$$f_{ij}^k \le (q^k - D_i)x_{ij}^k \quad (i = 0,...,t; \quad j = 0,...,n; \quad j \ne i; \quad k = 1,...,m) \tag{14}$$

$$D_j x_{ij}^k \le f_{ij}^k \quad (j = 1,...,t; \quad i = 0,...,n; \quad i \ne j; \quad k = 1,...,m) \tag{15}$$

$$D_i x_{ij}^k \le f_{ij}^k \quad (i = t+1,...,n; \quad j = 0,...,n; \quad j \ne i; \quad k = 1,...,m) \tag{16}$$

$$f_{ij}^k \le (q^k - D_j)x_{ij}^k \quad (j = t+1,...,n; \quad i = 0,...,n; \quad i \ne j; \quad k = 1,...,m) \tag{17}$$

Constraints (1) mean that no more than m vehicles (fleet size) depart from the depot. Constraints (2) are the flow conservation on each node. Constraints (3) guarantee that each customer and supplier is visited exactly once. Constraints (4) and (5) ensure that no vehicle can be overloaded. Constraint (6) guarantees that customers are not visited after any suppliers (backhauls), while constraint (7) avoids empty running on the way out. Starting service times are calculated in constraints (8) and (9). These constraints also avoid subtours. Time windows are imposed by constraints (10). Constraints (11) avoid exceeding the maximum allowable driving time. Balance of flow is described through constraints (12) and (13). Constraints (14)-(17) are used to restrict the total load a vehicle carries.

The goal of the problem is to construct several routes minimizing the sum of internal and external costs. The internal costs (IC) associated with a given route is composed of five major items: costs of driver (DRC), energy costs (ENC), fixed cost of vehicles–investment, inspection, insurance- (FXC), maintenance costs (MNC) and toll costs (TLC). In addition, the external costs (EC) and social effects of transportation activities are considered. They are composed of: climate change costs (CCC), air pollution costs (APC), noise costs (NSC) and accidents costs (ACC).

$$\text{Minimize } IC + EC = (DRC + ENC + FXC + MNC + TLC) + (CCC + APC + NSC + ACC) \tag{18}$$

The mathematical forms of the aforementioned components shown in Equation (18) are presented bellow.

$$DRC = \sum_{k=1}^{m} p^k y_0^k \tag{19}$$

$$ENC = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \ne i}}^{n} \sum_{k=1}^{m} \sum_{r=1}^{R} fc^r \delta^{kr} d_{ij} (fe^k x_{ij}^k + feu^k f_{ij}^k) \tag{20}$$

$$FXC = \sum_{i=1}^{n} \sum_{k=1}^{m} fx^k x_{0i}^k \tag{21}$$

$$MNC = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \ne i}}^{n} \sum_{k=1}^{m} mn^k d_{ij} x_{ij}^k \tag{22}$$

$$TLC = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \ne i}}^{n} \sum_{k=1}^{m} tl_{ij} x_{ij}^k \tag{23}$$

$$CCC = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \ne i}}^{n} \sum_{k=1}^{m} \sum_{r=1}^{R} pe^{CO2} \delta^{kr} ef^{CO2,r} d_{ij} (fe^k x_{ij}^k + feu^k f_{ij}^k) \tag{24}$$

$$APC = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \ne i}}^{n} \sum_{k=1}^{m} \sum_{r=1}^{R} \sum_{t=1}^{T} \sum_{p=1}^{P} pe^p \delta^{kr} \gamma^{kt} ef^{p,t} d_{ij} x_{ij}^k \tag{25}$$

$$NSC = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \ne i}}^{n} \sum_{k=1}^{m} ne \, d_{ij} f_{ij}^k \tag{26}$$

$$ACC = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \ne i}}^{n} \sum_{k=1}^{m} ae \, d_{ij} f_{ij}^k \tag{27}$$

The set of parameters used in the above expressions are:

- p^k: pay of driver k per unit time
- fc^r: unit cost of fuel type r
- fe^k: fuel consumption for the empty veh. k
- feu^k: fuel consumption per unit of additional load in vehicle k
- δ^{kr}: equal to 1 if veh. k uses the fuel type r
- fx^k: the fixed cost of vehicle k
- mn^k: costs of preventive maintenance, repairs and tires per kilometre of vehicle k
- tl_{ij}: costs of tolls associated with arc (i,j)
- pe^{CO2}: unit price per ton of CO_2 emitted
- $ef^{CO2,r}$: emission factor, amount of CO_2 emitted per unit of fuel r consumed
- pe^p: the unit price per ton of the pollutant p emitted
- $ef^{p,t}$: amount of pollutant p emitted from tech. vehicle t per km travelled
- γ^{kt}: equal to 1 if veh. k belongs to tech. t
- *(ne; ae)*: costs of (noise emissions; accidents) per ton of load carried and per km travelled

5 ILLUSTRATIVE EXAMPLE

In this section, we use a four-node illustrative example to show the differences between using three objective functions: minimizing the total distance travelled (1), minimizing the total internal costs (2) and minimizing the total internal and external costs (3). We also study the traditional CVRP with Heterogeneous Fleet (a), versus the effect of adding Backhaul (b), adding also maximum allowable driving Time (c), and adding also Time Window (d). We solve 12 instances.

We consider the four node network of Figure 1, with 3 different vehicles at node 0 to serve customers 1, 2 and 3. We consider an average speed of 50 km/h on each arc. Then the driving times t_{ij} between nodes are 1, 2 and 2.24 hours, depending on the length of the arc. We assume a homogeneous load demanded by each node as D_i=8 ton. Service times are set to s_i^k=1 hour in all nodes by all vehicles, and there are no toll costs.

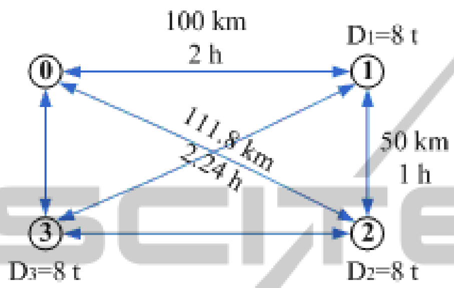

Figure 1: Four-node example.

Table 1 shows the parameters associated to each vehicle of the fleet. Table 2 shows the parameters associated to fuel unit costs, external unit costs and emission factors of vehicle types used.

As mentioned above, 12 instances are modelled using the MILP problem. In case (b) we consider a backhaul in node 2 with a demand of D_2=-8 ton. In case (c) we also assume a maximum driving time for each vehicle of 8 h. And finally in case (d) we also set a time window in node 1 of [3h, 5h].

We have used CPLEX 11.1 with its default settings to solve the 12 MILP instances. Eight different solutions have been found (Table 3).

The solutions associated to each instance and the objective functions are illustrated in Table 4.

Table 1: Fleet parameters.

Vehicles (k)	1	2	3
q^k (tons)	9.5	18	9.5
p^k (€/h)	19.89	21.40	19.89
Type of fuel (r)	Diesel	Diesel	Diesel
fe^k (l/100km)	17.50	19.80	17.50
feu^k (l/ton·100km)	1.05	0.75	1.05
fx^k (€/day)	42.65	54.60	42.65
mn^k (€/km)	0.0590	0.0787	0.0590
Technology (t)	Rigid; 12-14_t; Euro_IV t=2	Rigid; 20-26_t; Euro_IV t=3	Rigid; 12-14_t; Euro_II t=1

Table 2: Unit costs.

fc^{DIESEL} (2010€/l)		0.9009	
pe^{CO2} (2010€/ton)		25	
$ef^{CO2,DIESEL}$ (kg/l)		2.67	
Pollutant (p)	NOx	NMVOC	PM
pe^p (2010€/ton)	3439.8	529.2	76337.1
$ef^{p,1}$ (gr/km)	5.50	0.207	0.1040
$ef^{p,2}$ (gr/km)	2.65	0.008	0.0161
$ef^{p,3}$ (gr/km)	3.83	0.010	0.0239
ne (2010€/ton-km)		0.00648	
ae (2010€/ton-km)		0.00635	

Table 3: Different optimal solutions.

Sol.	Veh.	Optimal Route	Load (ton)	Arrival Time (h.)
#1	1 2	0-3-0 0-2-1-0	8-0 16-8-0	3 7.24
#2	2	0-3-1-2-0	16-8-0-8	9.48
#3	1 3	0-3-0 0-1-2-0	8-0 8-0-8	3 7.24
#4	1 2	0-1-0 0-3-2-0	8-0 8-0-8	6 7.24
#5	1 2	0-3-0 0-1-2-0	8-0 16-8-0	3 7.24
#6	1 3	0-1-2-0 0-3-0	8-0-8 8-0	7.24 3
#7	1 3	0-1-0 0-3-2-0	8-0 8-0-8	6 7.24
#8	1 3	0-3-2-0 0-1-0	8-0-8 8-0	7.24 6

Table 4: Solutions and values of the three objective functions for all the instances.

Inst.	Sol.	O.F. 1 Total Distances	O. F. 2 Total Internal Costs	O. F. 2 Total Costs
1a	#1	361,8 †	419,5	463,9
1b	#2	323,6 †	358,3 †	402,0 †
1c	#3	361,8 †	387,2 †	428,1
1d	#4	461,8 †	498,6	538,6
2a	#5	361,8 †	418,2 †	460,0 †
2b	#2	323,6 †	358,3 †	402,0 †
2c	#6	361,8 †	387,2 †	425,2 †
2d	#7	461,8 †	468,6 †	511,6
3a	#5	361,8 †	418,2 †	460,0 †
3b	#2	323,6 †	358,3 †	402,0 †
3c	#6	361,8 †	387,2 †	425,2 †
3d	#8	461,8 †	468,6 †	510,5 †

† Optimal solution with that Objective Function

6 ANALYSIS OF RESULTS

Some implications of the results presented in Table 4 are as follows.

Optimal solutions which consider the traditional objective function of minimizing total distance travelled (Sol#1 to Sol#4) are not optimal in some cases when the objective function includes costs' parameters. But optimal solutions which consider internal and external costs in the objective function (Sol#5, #2, #6 and #8) are also optimal minimizing distances or internal costs. The reason is that minimizing internal costs is quite similar to minimizing distances.

When a heterogeneous fleet is considered, adding external costs implies the selection of the less pollutant vehicles or the assignment of longer routes to those vehicles (Sol#7 vs. Sol#8), maintaining minimum total internal costs.

Depending on the type of VRP, the analysis of performance measures must be different. Solutions including backhauls reduce all the costs (see Table 4, Inst.*b* vs. Inst.*a*). But adding time constraints increase the costs (see Table 4, Inst.*d* or Ins.*c* vs. Inst.*b*). Using the total costs allows comparing different solutions and selecting the most appropriate. For example, Sol#8 is better than Sol#7 for the external cost, and also Sol#7 is better than Sol#4 for the internal and external costs.

7 CONCLUSIONS

In this paper, a new mixed-integer linear programming model for the Vehicle Routing Problem with some realistic assumptions (Heterogeneous Fleet, Time Windows and Backhauls) is presented with a broader objective function that accounts not just for the internal costs, but also for external costs. With this model, transportation companies can select the most appropriate vehicles, determine the routes and schedules to satisfy the demands of the customers, reduce externalities and achieve a more sustainable balance between economic, environmental and social objectives.

An illustrative example with four nodes and three different vehicles has been presented. 12 instances of the 4-node example have been solved using three objective function and four variants. 8 different optimal solutions have been obtained and they have been compared. Solution with the lowest values of the total costs is the dominant solution and must be selected.

Further research leads to the application of the model to realistic numbers of customers. In larger instances the development of heuristic algorithms such as tabu search methods are needed.

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