A Comparison of Homogeneous and Heterogeneous Vehicle Fleet Size in Green Vehicle Routing Problem

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Abstract. To balance a fragmented logistics organization, Small and Medium Enterprises have to find collective solutions to decrease their environmental impact. Especially when the demand at each producer takes the form of small packages and low quantities this paper examines the effect of the introduction of a consolidation center on the environmental issue. Therefore, the Fleet Size and Mix Vehicle Routing Problem (FSMVRP) was adapted in order to minimize CO2 emission. An exact mathematical formulation of the extended problem was developed to investigate the difference between homogeneous and heterogeneous fleet size on the environmental issue. Computational experiments for the problem formulation are performed using CPLEX and give a solution of a small instance to illustrate the problem. A case study focuses on optimal parcel picking up, from many producers to a common depot in the agri-food sector.

Keywords: Sustainable routing problem, Fleet Size and Mix Vehicle Routing Problem, Environmental objectives, Pickup optimization, Agri-food sector.

Introduction

By enabling a closer relationship between all supply-chain partners, Supply Chain Management (SCM) achieves cost reductions and revenue enhancements, as well as flexibility in dealing with supply and demand uncertainties [1, 2]. Due to the market evolution and a constant pressure of European regulations companies are pushed now to integrate environmental concerns in their supply chains in line with sustainable objectives [3, 4]. At the same time, new logistics requirement, such as quick response, high delivery frequency and small quantities increase the complexity of flow management and explode logistics costs.

In this situation, SME's with a lower maturity level in supply chain, have difficulties to integrate green approach in their logistics activities. This is why the consolidation of goods appears as a good way to improve the economic and environmental efficiency of flow management and emphasizes the importance of the Vehicle Routing Problem-VRP [3]. The traditional VRP is usually based on a homogeneous fleet size problem and becomes more complex when the vehicle fleet is heterogeneous [5]. Vehicles of different carrying capacities provide capacity according to the customers' varying demand, in a more cost effective way [6, 7], and this configuration has multiple advantages in real life [8].

B. Grabot et al. (Eds.): APMS 2014, Part II, IFIP AICT 439, pp. 450–457, 2014.

The objective of this research is to optimize the logistics' environmental impact of a set of small producers in the agri-food sector. Depending on the amount of products to be collected from these different producers and transported to a common distribution center, this paper investigates the difference between homogeneous and heterogeneous fleet size on the CO2 emission. Thus, the problem that is considered in this paper is a Fleet Size and Mix Vehicle Routing Problem (FSMVRP) that is adapted to take into account the environmental objectives, while focusing on the collect of products from several manufacturers to a common depot.

1 FSMVRP Problem: Definition and Overview

The VRP assumes that there is a limited fleet, each vehicle with the same capacity, whereas the FSMVRP determines the number and the type of vehicles in an unlimited fleet [9]. Thus, the usual objective is to minimize the sum of vehicle acquiring costs (Fixed Cost) and the routing costs (Variable Cost) [7]. Generally, the environmental aspects have been addressed in the literature in some variants of VRP, namely, Green VRP (G-VRP) [10], Pollution Routing Problem (PRP) [11] and Emissions VRP (E-VRP) [12], and consider two main objectives: the minimization of energy (fuel) consumption and CO2 emissions. Since our research mainly focuses on the environmental issues of routing problem while using heterogeneous fleet, a review of literature that deals with vehicles of different types and environmental aspects has been conducted

1.1 Overview of FSMVRP Problem with Green Objectives

Recent research on FSMVRP attempts to assimilate so called "environmental" aspects into normal routing models. Minimizing transportation related emission (especially CO2) and energy consumption instead of the driving distances are significant integration approaches [13]. In their work [14], authors showed how changes in fleet management were introduced as well as the implementation of a methodology to solve vehicle routing problems with environmental criteria minimization but limited to vehicle types with the same characteristics. In their case, as the payload carried on arcs cannot be known in advance, the authors have to settle for estimated values of the emission factors.

In another way, authors in [15] employ the COPERT model presented in [16] to estimate the fuel consumption. Their model is based on the payload and gradient correction factor for heavy duty vehicles. These authors define different vehicle classes and discuss the influence of gradient and payload on CO2 emissions for each vehicle class. Nevertheless, there is no mixed fleet considered in this paper since the analysis is done for several vehicle classes independently.

Unlike the previous scientific work, [13] introduced the fuel consumption minimization of vehicle routing problem with different vehicle classes. Their model minimizes fuel consumption instead of driving distance by offering the possibility of using several types of vehicles. The authors compared their model to the traditional VRP. They found that a significant amount of reduction is possible through the use of a heterogeneous fleet of vehicles and established a direct link between fuel consumption and CO2 emissions. However their model did not provide a minimization function of CO2 emissions in the routing problem.

A detailed literature review leads to conclude that there is need to define a FSMVRP that integrate green objectives, which will be stated in following section.

2 Modeling of FSMVR with Green Objectives

This section presents a new version of the traditional approach of the fleet size and mix vehicle routing problem. This new model reduces environmental costs by enhancing the use of different vehicles types.

2.1 General Assumptions and Problem Formulation

As in normal VRPs, we assume that there is only one depot in our system. The schedules are one-time plans and the time horizon is assumed to be a single period e.g. one day. It is assumed that all goods are conditioned in parcels with different volumes and weights. The fleet consists of vehicles of various types with differing curb weights and load capacities.

All vehicles start their routes at time zero. Each vehicle starts and returns to the depot upon completing its respective trips. At each stop, the vehicle has a loading time which is relative to the vehicle type. There is a restriction on the duration of each route. There is limitation on the vehicle speeds, for regional delivery, average vehicle speed of 45 km/h is considered.

The problem is defined as complete graph $G(N, A)$ where $N=\{0\}U\{1,\dots,n\}U\{n+1\}$ defines the set of different nodes and $\{0\}$ and $\{n+1\}$ represent the depot and A is the set of arcs between each pair of nodes. The set of manufacturers is represented by $N_c = \{1,\dots,n\}$. For every arc (i,j) in A, the distance between nodes i and j is defined as d_{ij}. For all $i \in N_c$, there is a positive demand of q_i to be satisfied. For each manufacturer, there is an associated loading time which is directly proportional to the vehicle type but not to the demand of that manufacturer, because we are dealing with very small demands which are delivered in parcels. The demand at the depot is considered to be zero ($q_0 = 0$; $q_{n+1} = 0$). Each manufacturer should be visited once by one vehicle and routes must start and finish at the depot. An unlimited heterogeneous fleet of vehicles is available. This fleet is composed of $V = \{1,\dots, K\}$ different vehicle types, each with a different capacity (weight and volume) that must not be exceeded.

2.2 Environmental Objective

As point out by [12] and [14], CO2 emissions depend on distance traveled, the weight carried by the vehicle, curb weight of the vehicle and its average speed. This indicates that using vehicles of adequate size reduces CO2 emissions. Further, to calculate CO2 emissions, the distance in the whole logistics network must be modeled: among producers themselves, as well as the distances between depot and producers. The formula given by [17- 19] was adapted to calculate the CO2 emissions based on vehicle type k and average speed.

$$\boldsymbol{\varepsilon}(d, X^P, k) = d * \left[(\boldsymbol{E}^k_{full} - \boldsymbol{E}^k_{empty}) * \frac{X^P}{\boldsymbol{C}^P_k} + \boldsymbol{E}^k_{empty} \right] \quad (1)$$

With:
d : distance traveled ; X^P : Total weight of transported parcels
C_k^P: Weight capacity of type k vehicle.
E_{full}^k : Emission of type k vehicle in full load
E_{empty}^k : Emission of empty type k vehicle.

The calculation of emission E_{full}^k and E_{empty}^k according to different transport capacity are based on the data provided by [18, 19] and can be calculated by knowing the value of the average speed of a route.

To consider the emission due to a vehicle manufacturing, we have developed a formula to calculate CO2 emissions:

$$\boldsymbol{\varepsilon}(d, X^P, k) = d * \left[(\boldsymbol{E}_{full}^k - \boldsymbol{E}_{empty}^k) * \frac{X^P}{\boldsymbol{C}_k^P} + \boldsymbol{E}_{empty}^k + \frac{\boldsymbol{E}_{manufacturing}(k)}{\boldsymbol{D}\,(\mathrm{k})} \right] \quad (2)$$

Where:
$\boldsymbol{E}_{manufacturing}$: CO2 emission issued from manufacturing type k vehicle [18].
$\boldsymbol{D}$ (k) : maximum number of kilometers of type k vehicle in its whole life.

From emission function (equation 2), we define the objective function to optimize:

$$Minimize \sum_{k \in V} \sum_{(i,j) \in A} d_{ij}\, a_k\, x_{ij}^k + d_{ij}\, b_k\, y_{ij}^k \qquad (3)$$

Where: $a_k = \left[E_{empty}^k + \frac{E_{manufacturing}(k)}{D\,(\mathrm{k})} \right]$; $b_k = \left[\frac{E_{full}^k - E_{empty}^k}{C_k^P} \right]$

This objective is divided into two parts: the first determines the CO2 emissions related to the movement of an empty vehicle while the second calculates emissions related to the weight loaded. The CO2 emissions are calculated with the travel distance, and vehicle specific conditions such as the gross weight of the vehicle (including the curb weight and the load carried) and the vehicle speed. Note that the factor "load" plays a significant role in our environmental model and it is this factor which determines the direction of vehicle route.

To assess economic and social costs of environmental optimization solutions, we adopted these equations:

- Economic function:

$$Cost(€) = \sum_{k \in V} \sum_{j \in N} f_k x_{0j}^k + \sum_{k \in V} \sum_{(i,j) \in A} \alpha_k\, d_{ij}\, y_{ij}^k + \sum_{k \in V} \sum_{(i,j) \in A} \beta_k\, d_{ij}\, x_{ij}^k + \sum_{k \in V} \sum_{(i,j) \in A} \delta_k\, y_{ij}^k \quad (14)$$

- Social function:

$$Social\ cost = \sum_{j=1}^{N} Q_k\, x_{0j}^k * \sum_{k \in V} \sum_{(i,j) \in A} d_{ij}\, x_{ij}^k$$

With:
$\boldsymbol{y_{ij}^k}$: flows on arc *(i, j)* loaded on type k vehicle; $\boldsymbol{d_{ij}}$= distance of the arc *(i, j)*
$\boldsymbol{x_{ij}^k}$ = 1 if type k vehicle is assigned to *(i, j)*, and 0 otherwise.

n = number of manufacturers (nodes) ; K = number of vehicle types;
Q_k = Total authorized weight of a type k vehicle $(Q_1 < \ldots < Q_K)$;
f_k = fixed cost of a type k vehicle $(f_1 < \ldots < f_k)$; β_k = cost /km of a type k vehicle;
α_k = cost /ton.km of a type k vehicle ; δ_k = cost /ton of a type k vehicle;

The first part of the economic function gives the total fixed cost of the vehicles used and the others parts give the total variable routing cost. To appraise social impacts in our model, we consider parameters like traveled distance and the number and the size of used vehicles in the routing plan as a social indicator that can give us an idea of the non-measurable social indicators (Accident risk, noise and congestion).

3 Case Study

In order to test the model, we define a case study based on the data coming from the field. A collect center located in Saint-Etienne processes every day a pickup of parcels from different manufacturers. In a given day, 10 addresses are visited, located around the depot. The demand vector is given by table 1.

Table 1. Manufacturer's demand

Manufacturer	1	2	3	4	5	6	7	8	9	10
Demand (Ton)	0.09	0.11	0.07	0.5	0.7	0.03	0.11	0.06	0.05	0.6

3.1 Optimization Approach

First, the mathematical model is programmed in CPLEX. Then, MAPPOINT software is used to represent manufacturers and depot locations geographically. Then, the software provides a distance matrix between the various locations according to their address. Then, this distance matrix with other data from the case study are introduced in the model in the optimization software CPLEX. The execution of our optimization program provides the optimal routes according to environmental criteria. To operate our case study, we used a set of parameters, summarized in table 2:

Table 2. Parameters of optimization (adapted from [18])

Category	**Type of vehicles**	**Total authorized weight (ton)**	**Useful load (ton)**	**Cost/km**	**Cost/ton**	**Fixed Cost**	E^k_{Empty} **(g/CO2)**	E^k_{full} **(g/CO2)**	$E_{manufacturing}$ **/km**	**Unloading time (min)**
LDV*	1	1.5-2.5	0.7	0.15	0.04	104.84	68.4	68.4	8.3	7
HDV**	2	3.5	1.4	0.23	0.05	111.58	100.9	101	10.5	10
HDV**	3	5-6	2.84	0.25	0.07	111.58	107	154	14.2	17

*LDV: light duty vehicles ** HDV: heavy duty vehicles

We would like to point out that only diesel engines conforming to the most recent engine standards were considered. To ensure optimal service to producers, the constraint of maximum duration of 4 hours was introduced for vehicle excursions.

3.1 Results

Our environmental optimization model in this case study presents the following results depending on fleet composition:

Table 3. Summary of results

		DC	*Environmental optimization*			
	Fleet	Type 1 (Best fleet)	Heterogeneous	Homogeneous		
			Type (1; 2; 3)	Type 1	Type 2	Type 3
Assessment	Economic	262.2	110.73	129.97	91.158	117.52
	Environmental	**17106**	***11142***	**11237**	**13665**	**14282**
	Social	4460.6	524.3	1173.6	859.39	1225.9
	Distance	223.03	134.3	146.7	122.77	111.45
	Number of routes	**10**	**3** : 2 of type 1 and 1 of type 2	**4**	**2**	**2**

Routes relevant to the use of different fleets are summarized in the following table:

Table 4. Routes of various scenarios

Fleet	*Composition*	*Routes*
Homoge -neous	Type 1	Route 1: (0,5,0); Route 2: (0,10,0); Route 3: (0,1,4,3,0); Route 4: (0,9,2,7,6,8,0);
	Type 2	Route 1: (0,2,7,6,8,5,0); Route 2: (0,9,3,1,4,10,0)
	Type 3	Route 1: (0,9,3,1,4,10,5,0); Route 2: (0,2,7,6,8,0)
Hetero-geneous	Type (1; 2; 3)	Type 1: Route 1 (0,9,2,7,6,8,0); Route 2 (0,1,4,3,0)
		Type 2: Route 1 (0,10,5,0)
		Type 3: No Route (Type not used)

For the case study discussed, the model gives different results depending on the fleet composition. First, the basic scenario with direct collect (DC) from the producers to the depot has to be assessed. In direct collect scenario, the use of a homogeneous fleet of type 1 vehicles gives better results than homogeneous fleets that consist sequentially of type 2 and type 3 vehicles.

The first finding is that environmental optimization for vehicle routing gives best results than direct collection scenario, whatever the composition of the fleet used and whatever the assessment criterion. This is explained by the fact that direct collection scenario requires more vehicles (10 vehicles) and travels longer distances.

The second important point with this model is that the use of a heterogeneous fleet gives the best environmental results and a good compromise of economic and social cost than the use of homogeneous fleet. Indeed, the use of a homogeneous fleet of type 2 vehicles significantly decreases the economic cost, but explodes at the same time the environmental and social costs. And in the same way, using a fleet of type 1 vehicles reduces the environmental cost but not the economic and social costs. The same remark can be made for the use of a fleet vehicle with type 3. Whereas the use of a heterogeneous fleet minimizes the environmental cost, while providing a great compromise for the economic and social cost. Another observation concerning environmental optimization is that routes to take depend on fleet composition.

4 Conclusion

The optimization of freight distribution for Small and Very Small Enterprises needs an improved shared logistics scheme to meet sustainable development requirements. This is especially true for agri-food supply chains, where the logistics flows of each company are characterized by small quantities, low volumes, and required to be delivered quickly. Most of the time, vehicles used for delivery are not adapted, too big, with a very low load rate, and therefore, the performance of their upstream logistics are not in line with the green objectives.

In this paper, the distribution network was designed with a single distribution center and the routing problem was solved taking into consideration the environmental pillar of sustainable development. Due to the constraints of low volume and limited time for delivery, the Fleet Size and Mix Vehicle Routing Problem (FSMVRP) was studied. Starting from the literature on this topic, new green objective functions were developed: the aim was to focus on CO2 emissions minimization. Based on literature, a new function was developed to take into consideration the type of vehicle and the transported weight.

The aim of this paper was to prove the importance of the choice of the type and number of vehicles in environmental optimization, and that routes depend on fleet composition. Instead of having a sole assessment criterion, this paper suggests to evaluate results on three criteria, economic, environmental and social.

A linear multi-objective programming optimization model was developed that compare optimal environmental solutions depending on the fleet composition. Unfortunately, due to long computational delays, this model can support only small instances. Clearly, this difficulty should be dealt with in future work. This work represents the first step to designing shared logistics schemes that fulfill the requirements of sustainable development.

Acknowledgment. Authors would like to thank Region Rhône-Alpes for its financial support (Research Cluster GOSPI).

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