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Multi-Criteria Optimization for Fleet Size with Environmental Aspects

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Abstract

This research concerns multi-criteria vehicle routing problems. Mathematical models are formulated with mixed-integer programming. We consider maximization of capacity of truck vs. minimization of utilization of fuel, carbon emission and production of noise. The problems deal with green logistics for routes crossing the Western Pyrenees in Navarre, Basque Country and La Rioja, Spain.
We consider heterogeneous fleet of trucks. Different types of trucks have not only different capacities, but also require different amounts of fuel for operations. Consequently, the amount of carbon emission and noise vary as well. Companies planning delivery routes must consider the trade-off between the financial and environmental aspects of transportation. Efficiency of delivery routes is impacted by truck size and the possibility of dividing long delivery routes into smaller ones.
The results of computational experiments modeled after real data from a Spanish food distribution company are reported. Computational results based on formulated optimization models show some balance between fleet size, truck types, utilization of fuel, carbon emission and production of noise. As a result, the company could consider a mixture of trucks sizes and divided routes for smaller trucks. Analyses of obtained results could help logistics managers lead the initiative in environmental conservation by saving fuel and consequently minimizing pollution.

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Keywords: Multi-Criteria Decision Making; Vehicle Routing; Green Logistics; Heterogeneous fleet.

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1. Introduction

In this paper we consider the group of green vehicle routing problems, specifically the maximization of capacity of trucks vs. the minimization of utilization of fuel, carbon emission, and noise production. We consider heterogeneous fleet of trucks. Different types of trucks have not only different capacities, but also require different amounts of fuel for operations. Consequently, the amount of carbon emission and noise vary as well. Companies planning delivery routes must consider the trade-off between the financial and environmental aspects of transportation. Efficiency of delivery routes is impacted by truck size and the possibility of dividing long delivery routes into smaller ones.

Because road transportation is a leading way of transporting goods all around the world, truck emissions must be controlled. The environment is highly valued within the trucking industry; over the years the there have been several efforts to reduce fuel consumption and emissions. Many more steps can be taken, such as designing more efficient engines, optimization of vehicles and trains, and changing vehicle total weight. For example, Volvo aimed to reduce fuel consumption by approximately 38% from 1980 to 2009 (Volvo, 2014). Similarly, Mercedes-Benz has proved their evolution from 1996 till 2016, during which they have reduced heavy truck fuel consumption by 22%, a reduction of at least 50 million tons in the CO_2 in Europe (Daimler, 2016).

Additional factors to consider concerning truck emission reduction include payload, trailer cargo volume, and maximum speed limits. These factors differ notoriously in the European and US markets. Maximum speed limits are higher in the US than in Europe. Similarly, US trucks can legally transport 21% more volume than European trucks. However, EU trucks emit 16% less CO_2 overall than US trucks (ACEA/EAMA, 2016).

Computational results based on formulated optimization models show balance between fleet size, truck types, utilization of fuel, carbon emission, and noise production. As a result, the company could consider a mixture of trucks sizes and divided routes for smaller trucks.

For computational experiments, exact solution methods are applied for finding suboptimal solutions. The CPLEX solver, using the AMPL programming language, is used to solve such models (Fourer et al., 1990). This research has been performed using real data from the Spanish grocery company Eroski. This research problem deals with green logistics for routes crossing the Spanish regions of Navarre, Basque Country and La Rioja. The results of the current analysis may be helpful for logistics managers to lead the initiative of constructing routes, which have a lower environmental impact.

1.1. Road transportation

Road transportation is both important for economic development and harmful to the environment because of externalities such as pollution and noise (Koç et al., 2016; Kovacs et al., 2015, Grafton et al., 2004). For many years, the planning of freight transportation by road mainly focused on cost minimization. Increasing concern for the environment has recently led logistics managers and freight carriers to focus their attention on the formulations of transportation problems that include environmental aspects of transportation (Koç et al., 2016; Demir et al., 2014a; Sawik et al., 2017a, 2017b, 2017c, 2016a, 2016b, 2015).

1.2. Vehicle Routing Problem

The vehicle Routing Problem (VRP) has been studied since 1959 with the objective to minimize the total distance travelled by all vehicles. There are several variants to the VRP (Toth and Vigo, 2014). These are formulated based on the nature of the transported goods, the quality of service required, and the characteristics of the customers and vehicles. Other problem variations were derived from this basic problem, such as VRP with time windows (VRPTW), capacitated VRP (CVRP), multi-depot VRP (MDVRP), site-dependent VRP (SDVRP), the open routing problem (OVRP), Cumulative VRP (CumVRP), and finally the green vehicle routing problem (G-VRP) which considers environmental aspects of transportation (Koç et al., 2016; Demir et al., 2014a, Gaur et al., 2013; Lin et al., 2014, Erdogan et al., 2012; Sawik et al., 2017a, 2017b, 2017c). Other studies concern variations of the VRP, such as Oberscheider et al., (2013), in which the problem is formulated as a multi-depot vehicle routing problem with pick-up and delivery and time windows (MDVRPPDTW).

For many years, the most important requirement has been to minimize the total distance travelled by vehicles or total time taken into the delivery (Juan et al., 2014). Nowadays, fuel consumption, reduction of pollution and noise, fleet size, and capacity are important parts of the final objective in VRPs. Bektas & Laporte (2011) present the Pollution-Routing Problem (PRP), an extension of the classical Vehicle Routing Problem (VRP) with a broader and more comprehensive objective function that accounts not just for the travel distance, but also for the amount of greenhouse emissions, fuel, travel times, and their costs.

1.3. Algorithms and Multi-Objective Approach

Different algorithms have been considered to solve these types of optimization problems (Bektas, 2006; Faulin, 2003). Christofides et al. (1981) formulated an optimization problem for transportation, which is referred to as the vehicle routing problem and is a generalization of the multiple travelling salesman problem.

Multi-objective models for transportation can be divided into three groups: transportation, traveling salesman, and vehicle routing problems (Sawik et al., 2017b). There are several ways to solve multi-objective transportation problems with environmental aspects (Demir et al., 2014a, Jabir et al., 2015; Qu et al., 2016; Sawik et al., 2015, 2017a, 2017b, 2017c, 2016a, 2016b).

1.4. Eroski Group

Eroski - a Spanish supermarket chain has provided the real input data for computational experiments. It belongs to the Spain's cooperative group Mondragon Corporación Cooperativa, which is also called Eroski Group (Grupo Eroski, 2016a). The Eroski Group is one of the leading chains of the Spanish retailing market. Currently Eroski is Spain’s fourth largest supermarket chain (Grupo Eroski, 2016b). It operates more than 800 supermarkets throughout Spain. The Eroski brand extends to some petrol stations and travel agencies in addition to supermarkets. The company was founded in 1969 in Spain as a co-operative between ten smaller consumer cooperatives in the region. Its headquarters is in Elorrio, Biscay. The name “Eroski” is a combination of the Basque words "erosi" (to buy) and "toki" (place), which can be translated as "buying place" (Grupo Eroski, 2016a).

2. Related Work

Recently there have been several publications of G-VRP models, in which authors include differently formulated environmental aspects of transportation. Munoz-Villamizar et al. (2017) assesses the implementation of a fleet of electric vehicles concerning the distribution of goods in an urban setting, aiming to reduce environmental impacts while maintaining a high level of service. An important review of the environmental impact caused by road transportation and the influence of route optimization is depicted in Demir et al. (2014a). Dominguez et al. (2016) discusses the multi-start algorithm for two-dimensional loading capacitated vehicle routing problem with a heterogeneous fleet. In Sawik et al. (2017a) the research on G-VRP is focused on distance travelled and the altitude difference within the obtained optimal route. Sawik et al. (2017c) presents the group of green vehicle routing problems with environmental monetary costs versus production of noise, pollution and fuel consumption.

2.1. Transportation Fleet Capacity vs. Number of Trucks

The parallel considerations of fleet capacity and number of trucks considered for transportation could help the decision maker save money by using optimal fleet size and the control percentage of load. The extent of used capacity for transported goods has strong environmental impact. Several recently published papers consider fleet capacity or size. Hoff et al. (2010) have done a comprehensive literature review of industrial aspects of combined fleet composition and routing in maritime and road-based transportation. Chien et al. (2014) presents fleet size estimation with heterogeneous road geometry of road sections, truck capacities, spreading patterns, and traffic speeds under different weather conditions and time periods of an event. A robust optimization approach for the mobile facility fleet sizing and routing problem under uncertainty was introduced in Lei et al. (2016). Koç et al.

(2016b) researched the impact of depot location, fleet composition, and routing on emissions in city logistics. In a recent paper, Cheng et al., (2017) investigate modeling a green inventory routing problem with a heterogeneous fleet. This research extends the conventional inventory routing problem by considering environmental impacts and heterogeneous vehicles.

2.2. Noise, Pollution and Fuel Consumption

A methodology for calculation of noise in transportation models is not obvious at first sight. Noise itself impacts the environment separately from pollution. Noise occurs only for short period of time accompanying the moving truck. Despite its temporary nature, noise is measurable and can be optimized in transportation models. According to research carried out by various scientists, vehicles carrying heavy goods generate between 88 and 92 dB of noise, and vehicles carrying light goods generate between 79 and 81 dB of noise (Cirovic et al., 2014; Murphy & Poist, 2003). Researchers from Japan, Great Britain and Serbia have used noise in the classification of vehicles.

Pollution and fuel consumption are popular concerns in green transportation literature (Ubeda et al, 2011; Suzuki, 2011; Lin et al., 2014; Demir et al., 2014b; Sawik et al., 2015, 2017a, 2017b, 2017c, 2016a, 2016b). Some publications consider these environmental aspects for sea (Lättila et al., 2013) or air transport (Chao, 2014). Zheng & Chen (2016) consider fleet replacement decisions under demand and fuel price uncertainties.

Table 1. New methodology for measuring fuel consumption [f_k^o, f_k] and CO_2 emission [e_k^0, e_k]

Level of vehicle load	**Empty [f_k^o, e_k^o]**	Percentage of load [f_k, e_k]	Full loaded
Weight laden [%]	**0.000**	1%	100%
Consumption (l/km)	**0.296**	0.00094	0.390
Fuel conversion factor [kg CO_2/l]	2.610		
Emission factor [kg CO_2/km]	**0.773**	0.775	1.018

Source: Calculated and prepared by Bartosz Sawik with information of Úbeda et al, 2011

Table 1. depicts the methodology of measuring fuel consumption and carbon emission. This methodology is introduced to determine the precise percentage of truck load and to build a linear objective function. Ubeda et al. (2011) proposed the methodology of measuring fuel consumption and carbon emission for 25%, 50%, 75% and full truck load. Unfortunately, the Ubeda et al. (2011) measuring method leads to a non-linear objective function. Consequently, modifications of Ubeda et al 2011 methodology have been implemented and presented in this paper.

3. Computational Experiments

The computational experiments were performed using the AMPL programming language and the CPLEX 11.0. solver with the default setting, on a MacBook Air laptop with Intel Core i7 processor running at 1.7GHz and with 8GB RAM.

3.1. Mathematical models

Several green vehicle routing multi-objective optimization models have been considered. The optimality criteria, which consider total capacity, fleet size, and environmental aspects including:

- noise
- pollution, defined as amount of CO_2 emissions
- fuel consumption

All considered models have linear objectives and constraints. The optimization models have mixed-integer programming formulations corresponding to the types of decision variables. The appropriate group of constraints is associated with the set of objectives.

Constraints for all multi-criteria objectives are formulated as follows:
- to ensure that all the vehicles begin and end their routes at the depot
- to guarantee that each node, except the depot, is visited by a single vehicle
- to assure that each node, except the depot, is linked only with a pair of nodes, one preceding it and the other following it
- to guarantee that no vehicle can be overloaded
- no vehicle exceeds the maximum allowable driving time per day

In addition to presented constraints all considered bi-criteria G-VRP models consist of the Miller-Tucker-Zemlin subtour elimination constraints (Sawik, 2016; Velednitsky, 2017).

The exact approach is applied for finding suboptimal solutions with use of CPLEX solver. These green vehicle routing mathematical models were formulated under assumption of existence of asymmetric distance-based costs and the use of a heterogeneous fleet.

3.2. Multi-Criteria Models

Formulations of selected multi-criteria optimization models are presented in this subsection. We consider the variation of the weighted-sum approach for bi-objective optimization models. The first objective is related to capacity or fleet size, and the second objective concerns the environment.

The following objectives are considered (Sawik, 2018):
- Maximization of total capacity vs. minimization of fuel utilization
- Maximization of total capacity vs. minimization of carbon emission
- Maximization of total capacity vs. minimization of production of noise
- Minimization of fleet size vs. maximization of total capacity

3.3. Real input data

This research has been focused on different points of Navarra, Basque Country, and La Rioja, where Eroski Group (Grupo Eroski, 2016a, 2016b) has its mains points of sale in that region. The depot of this area, Elorrio, Biscay, houses the warehouse of the goods that need to be transported. This means that Elorrio, the depot, is the first node taken by the trucks before transportation to the 27 other destinations, most of which are in Navarra. The delivery points are different villages in Navarra, La Rioja, and Basque Country, where Eroski Group owns different supermarkets and transportation is necessary.

3.4. Obtained results for multi-objective problems

Comparison of selected results obtained for multi-objective problems have been presented in Tables 2-3.

Table 2 shows the relationship between different formulated environmental criteria. The results shown in Table 2 are presented in increasing order according to distance and driving time requirements. Obtained values presented in Table 2 are for up to 95 trucks used for delivery. The order node within delivery networks differs with environmental criteria. It is possible to slightly control and limit carbon emissions and noise.

Table 3 presents selected extreme results, which show the relation between considered different criteria in bi-criteria G-VRP models and number of chosen trucks for delivery, corresponding fuel consumption, carbon emission, noise and amount of goods packed for chosen trucks of all types. Trucks have been chosen from heterogeneous fleet of different capacity and different fuel consumption, carbon emission and noise parameters. For comparison of results of chosen different types of trucks average usage of fuel, production of carbon dioxide and noise per truck is presented.

Table 2. Comparison of selected results considering different environmental criteria.

	Distance [km]	Driving Time [hours]	Average fuel consumption per truck [l/100 km]	Average carbon emission per truck [kg CO_2/km]	Average noise per truck [dB]	Total amount of goods [pallets]
Fuel consumption	17777	323	28	78	92	3444
Carbon emissions	18023	328	29	79	90	3444
Noise	18444	335	30	80	88	3444

Source: Original results obtained by Bartosz Sawik
The computational experiments were performed using the AMPL programming language and the CPLEX 11.0. solver with the default setting, on a MacBook Air laptop with Intel Core i7 processor running at 1.7GHz and with 8GB RAM

Table 3. Comparison of selected extreme results from bi-criteria G-VRP models.

	Average number of chosen trucks of all types	Average fuel consumption per truck [l/100 km]	Average CO_2 emission per truck [kg CO_2/km]	Average noise per truck [dB]
Maximization of total capacity vs. minimization of fuel utilization	88	28	74	90
Maximization of total capacity vs. minimization of carbon emission	89	28	75	92
Maximization of total capacity vs. minimization of production of noise	92	29	78	88
Minimization of fleet size vs. maximization of total capacity	95	30	80	89

Source: Original results obtained by Bartosz Sawik
The computational experiments were performed using the AMPL programming language and the CPLEX 11.0. solver with the default setting, on a MacBook Air laptop with Intel Core i7 processor running at 1.7GHz and with 8GB RAM

3.5. Central Processor Unit (CPU)

The computational experiments for the considered different sets of multi-objective green vehicle routing problems with the subtour elimination constraints found suboptimal solutions in most cases for given input data within 7200 CPU seconds.

4. Conclusions and Future Work

In this paper, we have discussed some green vehicle routing problems for optimal fleet size and required transportation tasks capacity. Multi-Criteria optimization models include environmental aspects considering fuel consumption, pollution, and noise. Thus, some mixed-integer programming formulations of multi-criteria vehicle routing problems have been considered. Some mathematical models were formulated under the assumption of the existence of asymmetric distance-based costs and the use of a homogeneous fleet. The exact solution methods were applied to find suboptimal solutions. Software usage to solve these models included the CPLEX solver with AMPL programming language.

All formulated and presented mixed integer multi-criteria mathematical programming models have linear objective and constraints with linear and integer decision variables. All presented results are suboptimal. Computational time for finding suboptimal solutions is less than 7200 CPU.

The obtained results show that it is possible to slightly control and limit carbon emissions and noise. There is a relationship between obtained fleet size, capacity, obtained distances, driving times, and obtained values of environmental objectives. This relationship proves the need for consideration of all these aspects of transportation together in multi-criteria models.

Based on obtained results the relation between size of truck (capacity and engine parameters) versus fuel consumption, carbon dioxide emission and noise is the following: larger trucks require less amount of fuel per km, produces less CO_2 emissions, but produces more noise.

In this study, the researchers used real data from a Spanish company of groceries called Eroski. The solved problems deal with green logistics for routes crossing the Spanish regions of Navarre, Basque Country, and La Rioja. Regarding future work, we are currently working on an extended version of this problem, which includes a heterogeneous fleet and a combination of the vehicle routing, and the portfolio problem.

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