

Multi-Objective Approach for Solving VRP with a Heterogeneous Fleet Powered by Different Energy Sources

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ABSTRACT

A solution method to the Multi-Objective Vehicle Routing Problem (MO-VRP) was applied to a real-case instance, aiming to minimize logistics costs, CO₂ emissions, and accident risks. Heterogeneous fleet comprising different vehicles powered by various energy sources, including battery, compressed natural gas, and diesel fuel, was considered. The *Augmented Weighted Tchebycheff* (AWT) method was selected to tackle the MO-VRP, and an enhanced Genetic Algorithm was employed as a heuristic to generate feasible solutions, which helped to warm-start the optimization process in the exact method when the model struggled to find solutions. The results showed that diesel trucks were the most economically viable, but Alternative Fuel Vehicles (AFVs) were preferred when prioritizing CO₂ emissions, achieving a 90% reduction. However, this led to a 35% increase in logistics costs. When accident risks were prioritized, they were reduced by 55%, while logistics costs enhanced by 60%. Finally, the approach proved to be useful in planning deliveries, considering the three objectives, due to its simplicity in generating solutions.

KEYWORDS. Multi-Objective Vehicle Routing Problem. *Augmented Weighted Tchebycheff*. Accident risk.

1. Introduction

The need for sustainable development has become increasingly urgent amid recent events such as rapid population growth, natural and social disasters, climate change, and many other reasons. Furthermore, sustainable development is important because the needs of the current generation must be met, but resources must also be guaranteed for the next generations [Dündar et al., 2021]. The Triple Bottom Line ("3BL") approach supports the concept of sustainability by promoting a balance between economic, social, and environmental aspects Elkington [2001]. In the Vehicle Routing Problems (VRP), Dündar et al. [2021] claim that the economic dimension remains the most extensively explored, while Ferreira et al. [2020] observe that risk is often underrepresented.

The quantity of CO₂ equivalent in the atmosphere could be understood as an indicative of global warming. According to the Sistema de Estimativas de Emissões e Remoções de Gases de

Efeito Estufa [SEEG, 2021], Brazil was responsible for the emission of approximately 2.4 billion tons of CO₂ equivalent in 2021, which represented an increase of 8% compared to 2019, the last year before the COVID-19 pandemic; and transportation sector contributed 8.5% of total CO₂ emissions in Brazil.

In the social dimension, Abdullahi et al. [2021] state that the risk of accidents is one of the most crucial social indicators in road transport. As reported by the Confederação Brasileira de Transportes [CNT, 2022], road accidents on Brazilian federal highways alone accounted for 64,447 incidents in 2022, resulting in 52,948 cases involving deaths or injuries and an estimated total cost of approximately 13 billion Brazilian monetary units.

In addition to considering logistic costs and accident risks, road freight transport companies must integrate environmental considerations into their decision-making processes. This includes prioritizing the reduction of greenhouse gas (GHG) emissions and incorporating alternative fuel vehicles (AFVs) alongside traditional diesel vehicles in their fleets. Studies on sustainable VRP are less common compared to the extensive research on the general VRP topic. However, they have gained notable attention in recent years.

In this way, the study focused on implementing multi-objective approach based on the *Augmented Weighted Tchebycheff* method to find efficient, non-dominated solutions for a VRP that simultaneously minimize carbon dioxide emissions and accident risks while maintaining efficient logistics and cost-effectiveness. The study focused on a real instance of a large retail chain whose depot and delivery cities are located in the macro-region of Campinas, state of Paulo, Brazil. This original problem were adapted to include a heterogeneous fleet comprising diesel-powered trucks, compressed natural gas (CNG) vehicles, and electric trucks. Therefore, the study seeks to identify the optimal mix of vehicles to use for deliveries while minimizing the 3BL of sustainability.

The main contributions of this study are: developing a MO-VRP to support decision-making in minimizing the three dimensions of sustainability; adding vehicles powered by different energy sources to a heterogeneous fleet; and, use the *Augmented Weighted Tchebycheff* method to handle the MO-VRP and generate efficient non-dominated solutions.

2. Methodology

Figure 1 illustrates the workflow of the analytical approach, where the highlighted processes indicate the contributions of this study to the literature. It was divided into four phases. The Phase 1 consists of defining the MO-VRP. In Phase 2, the enhanced Genetic Algorithm was implemented to generate feasible solutions to initiate the exact method. In Phase 3, the formulation of the *Augmented Weighted Tchebycheff* method was solved by *Gurobi 10.0.3*, where the first *lexicographic Pareto optimal solutions* were found by the CVRP Solver [Pessoa et al., 2020]. Finally, in Phase 4, the results are analysed to determine if the solution is suitable for the company's process.

The *Augmented Weighted Tchebycheff* formulation is represented by Expression 1, where $M = \{1, 2, 3\}$ denotes the set of three sustainability dimension, $\bar{f}_m(\mathbf{X})$ and λ_m is the objective function and weights of dimension m , respectively, and $0 \leq \lambda_m \leq 1$, and $\sum_{m \in M} \lambda_m = 1$. S is the set of feasible solution space, α is an auxiliary variable and ρ is a small positive number.

$$\begin{aligned}
 & \text{minimize } \alpha + \rho \sum_{m \in M} \bar{f}_m(\mathbf{X}) \\
 & \text{subject to } \mathbf{X} \in S \\
 & \quad \lambda_m \bar{f}_m(\mathbf{X}) \leq \alpha \quad \forall m \in M \\
 & \quad \alpha \geq 0
 \end{aligned} \tag{1}$$

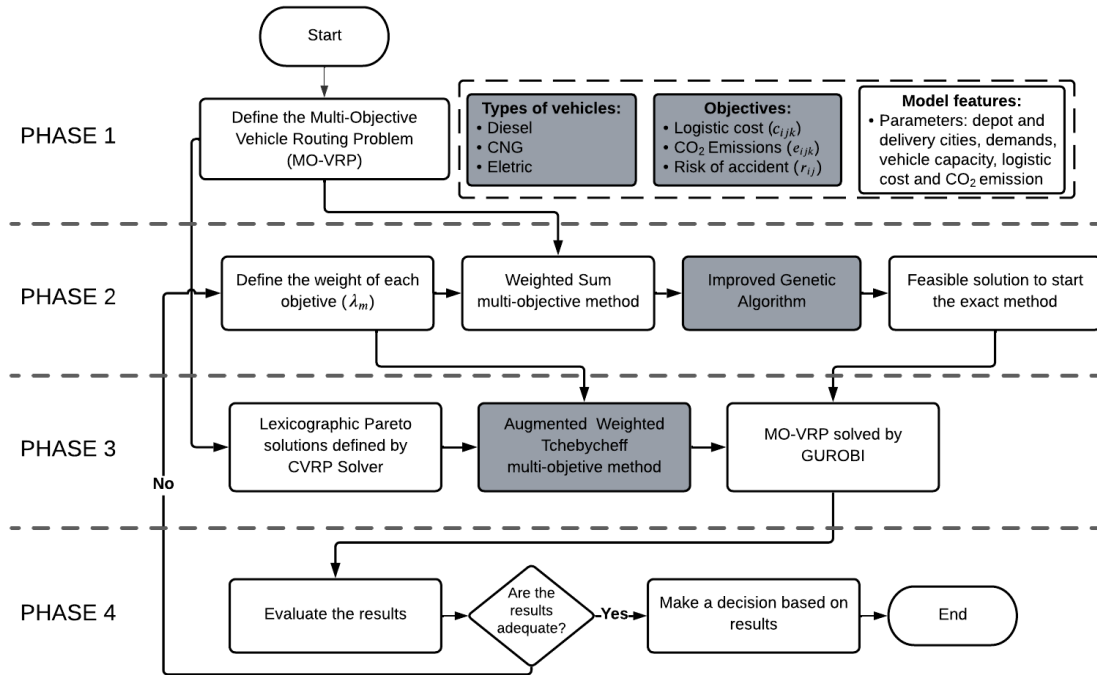


Figure 1: Workflow of the analytical approach.

The problem consists of 52 delivery points and 1 depot, and unlimited number of capacitated vehicles. The approach were implemented in python on a Intel(R) Xeon(R), 2.10GHz, 48 GB RAM, and 32 logical processors.

3. Results

The results are presented in Table 1 and show that electric vehicles were selected in most of the scenarios where minimizing CO₂ emissions was a priority, as they emit 0 kg/km of CO₂. However, in scenarios where minimizing logistic costs was the most important objective to minimize, the diesel fuel vehicles were preferred, demonstrating that these vehicles were the most economically viable.

The solutions obtained for each scenario were compared to the traditional method of optimizing routes, where minimizing costs (scenario L1) is preferable. In the scenario S2, where the minimization of CO₂ emission were preferable, almost 90% reduction in emissions were achieved, however logistics costs increased by 35%. In scenario S3, where minimizing risks were prioritized, risks were reduced by almost 55% causing a 60% increase in logistics costs.

Table 1: Solutions obtained for each scenarios.

Scenarios	Weights	Solutions			Quantity of vehicles		
		CO_2 emission (Kg)	Logistics (\$)	Risks (\$)	Diesel	CNG	Electric
L1	$\lambda_1 = 1.0$	5,613.52	7,506.13	37,534.72	14	0	0
	$\lambda_2 = 0.0$						
	$\lambda_3 = 0.0$						
S1	$\lambda_1 = 0.80$	5,924.35	6,279.89	35,293.74	10	0	5
	$\lambda_2 = 0.10$						
	$\lambda_3 = 0.10$						
S2	$\lambda_1 = 0.10$	283.39	8,355.17	31,987.89	1	0	14
	$\lambda_2 = 0.80$						
	$\lambda_3 = 0.10$						
S3	$\lambda_1 = 0.10$	3,694.60	9,534.11	28,959.97	6	0	8
	$\lambda_2 = 0.10$						
	$\lambda_3 = 0.80$						
S4	$\lambda_1 = 0.333$	2,623.77	7,995.87	31,499.25	5	0	10
	$\lambda_2 = 0.333$						
	$\lambda_3 = 0.333$						
S5	$\lambda_1 = 0.50$	3,675.72	7,272.12	32,746.57	7	0	8
	$\lambda_2 = 0.25$						
	$\lambda_3 = 0.25$						
S6	$\lambda_1 = 0.25$	1,260.02	8,095.63	31,615.70	3	0	12
	$\lambda_2 = 0.50$						
	$\lambda_3 = 0.25$						
S7	$\lambda_1 = 0.25$	3,387.66	8,699.27	30,365.55	5	0	10
	$\lambda_2 = 0.25$						
	$\lambda_3 = 0.50$						

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