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Minimizing carbon dioxide emission with distance for Tunisian public transportation via the dhouib-matrix-4-PMO method

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Abstract: One of the main causes of CO_2 emissions is believed to be urban transit. It is now crucial to create a sustainable transportation system to reduce its negative effects on the environment. Therefore, the primary objective of this research is to propose a strategy for reducing both distance and carbon dioxide emissions in the context of public bus distribution in Tunisia. In this paper, we propose a Multi-Objective Traveling Salesman Problem (MOTSP) model that considers environmental factors, along with a novel metaheuristic called Dhouib-Matrix-4-PMO. In fact, DM4-PMO is based on the initial enhancement of the new Dhouib-Matrix-4 (DM4) method and is adapted to generate Pareto non-dominated set solutions. The algorithm has been evaluated, and the results demonstrate the effectiveness of the proposed methodology.

Keywords: *Artificial intelligence in transportation, Intelligent transportation system, Metaheuristic, Operations research, Sustainability.*

1. Introduction

Growing discourse in recent years has focused on sustainability as a transdisciplinary idea that connects society, the environment, and the economy [1]. In fact, recently, environmental sustainability has received a lot of attention in both academic and industrial contexts. In response to rising carbon emissions and global warming, businesses need to make significant efforts to ensure environmental sustainability. Nowadays, a large number of businesses and organizations are being forced to lower their carbon emission values by global competitiveness [2]. Today, environmental concerns are a crucial component of any supply chain operation, making it essential for every company to adopt an environmentally responsible strategy.

While transport contributes positively to economic growth and the advancement of various industries, it can also have adverse effects on society, such as generating emissions, increasing traffic congestion, and more. Given the significance of these impacts, transport managers and experts are continuously working to enhance the efficiency of current systems and pursue sustainability objectives by implementing new policies.

Road transport is a significant contributor to air pollution, which greatly affects human health, especially in densely populated urban areas with high vehicle concentrations. Road transport must, therefore, be planned appropriately with the aim of keeping our environment as green as possible. Reducing transport fuel consumption and CO_2 emissions while optimizing transport operations is crucial. The primary goal is to design innovative mathematical models and optimization methods aimed at minimizing CO_2 emissions in the context of the Traveling Salesman Problem (TSP).

The Traveling Salesman Problem (TSP) is one of the most extensively researched and important challenges in combinatorial optimization [3]. The goal of the TSP is to determine the most cost-effective route that visits all cities in a given set, where the travel cost between each pair of cities is specified, and

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the journey must return to the starting point [4]. In our case, minimizing the environmental impact of CO_2 emissions will be our secondary objective, alongside minimizing distance. To achieve this, we will utilize the Multi-Objective Traveling Salesperson Problem (MOTSP) model where several objectives are considered such as minimizing time, cost, and risk. When the number of cities to visit is large, deterministic approaches are not feasible for solving the MOTSP. Therefore, heuristic and metaheuristic methods (such as the genetic algorithm, ant colony optimization, and particle swarm optimization) are employed to tackle this type of problem.

This research refines the recently developed metaheuristic Dhouib-Matrix-4 (DM4), which was created by Dhouib [5] to solve a real world MOTSP case study in Tunisia. The proposed method is namely DM4-PMO and generates the Pareto non-dominated solutions by minimizing the distance criterion with the carbon dioxide emission for the Tunisian's public transportation system.

The structure of the paper is as follows. A review of the literature is provided in the following section. In section three, the novel DM4 metaheuristic is introduced with a description of its enhancement version namely DM4-PMO for MOTSP. In section four, a Tunisian real-world case study is solved using the innovative DM4-PMO. In section five, the conclusion with the next recherché direction will be presented.

2. Literature Review

Numerous researchers have employed various heuristic and metaheuristic approaches to address the multiple Traveling Salesman Problem (mTSP) across different contexts. Currently, greenhouse gas emissions pose a significant challenge, as global climate change is one of the most pressing issues of our time. Nevertheless, carbon emissions are an inherent part of the transportation sector's production processes. Numerous publications in the literature discuss this problem. Due to the advantages of considering environmental factors, many supply chain executives and researchers are increasingly focusing on implementing green logistics.

2.1. MOTSP and Sustainable Transportation Systems

The growing significance of MOTSP models is evident from the increasing number of published articles. Our analysis indicates that these models are a major focus on the international stage. This study is based on data from the multidisciplinary database "SCOPUS," provided by the scientific publisher "Elsevier". Figure 1 reveals that the majority of scientific articles were published in the fields of engineering and mathematics.

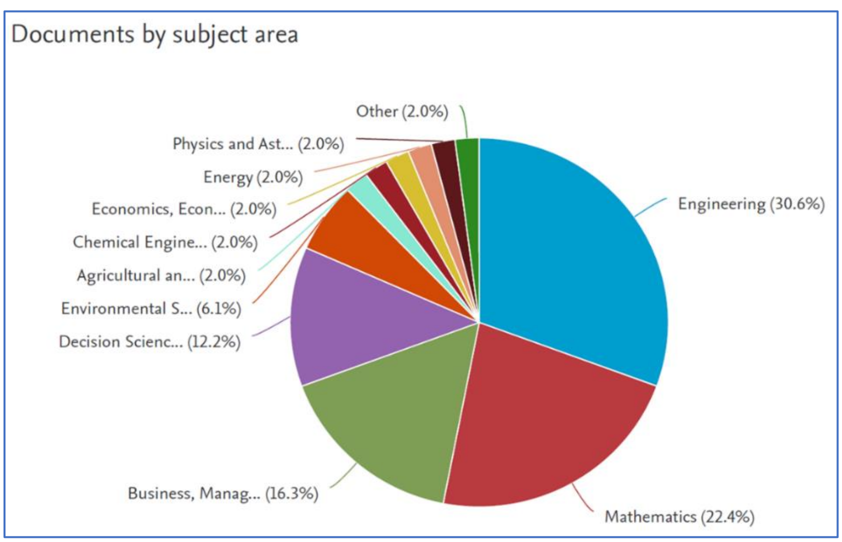

Figure 1.
Classifications of documents by subject area.

In this context, a brief review of the literature will be presented. In fact, Kakouei, et al. [6] proposed a model for estimating daily CO_2 emissions from road transportation, incorporating calculations for fuel efficiency, emission factors, and the emissions associated with each mode of transport. Moreover, Zhang, et al. [7] developed an environmental vehicle routing problem model utilizing a hybrid artificial bee colony algorithm, with CO_2 emissions serving as the primary metric. Through numerical experiments, the authors explored and evaluated several optimal solutions. Furthermore, Jabir, et al. [8] proposed a multi-objective green multi-depot capacitated vehicle routing optimization problem, for which they developed a mathematical model. The model incorporates both environmental and economic considerations. To solve the problem, they applied an Ant Colony Optimization technique combined with a hybrid meta-heuristic algorithm, utilizing a Variable Neighborhood Search (VNS) approach. The non-dominated Pareto optimal solutions were identified to address the proposed problem.

Elhassani, et al. [9] introduced and applied a nature-inspired metaheuristic method for optimizing the Traveling Salesman Problem (TSP). Their approach incorporated CO_2 emissions into the objective functions to consider the environmental impact of transportation. They conducted a comparative study using several benchmark TSPLIB instances. The results demonstrated that the genetic algorithm performs better with relatively high mutation and crossover rates, and that it evolves effectively with a moderate population size. Moreover, In Hernández - Pérez and Salazar - González [10] research, the authors' objective in the multi-commodity pickup-and-delivery traveling salesperson problem was to minimize the total travel distance. To address the capacitated pickup-and-delivery problem in large-scale instances, they proposed a hybrid heuristic technique. A numerical example is then provided to demonstrate the effectiveness of the proposed method.

The paper of Sawik, et al. [11] is focused on addressing multi-objective problems related to transportation and the traveling salesperson challenges. The computations are based on real-world data from a Spanish company's road freight operations. These models aim to minimize both the total distance traveled and CO_2 emissions. The models are solved using the CPLEX solver, which is implemented through the AMPL programming language. In the same context, Kaabachi, et al. [12] explored the bi-objective variant of the Generalized Traveling Salesman Problem with Time Windows (GTSPTW). This variant extends the traditional TSPTW by incorporating additional factors related to fuel consumption and emissions. The GTSPTW not only seeks to find the fastest route but also aims to minimize CO_2 emissions and fuel usage. To solve this model efficiently, they introduced an enhanced meta-heuristic approach that combined ant colony optimization with a local search algorithm.

Numerical experiments using benchmarks from the literature showed that fuel consumption and CO_2 emission costs constitute a significant portion of the overall cost. Jlassi, et al. [13] indeed examined the Dial-A-Ride Problem (DARP) as a specific case within the broader category of vehicle routing problems (VRP). Their study aimed at minimizing CO_2 emissions. Huang, et al. [14] conducted research on modeling and optimization approaches for network graph-based process planning problems aimed at reducing carbon emissions. In their study, they developed a novel mathematical model for process planning optimization, where parts are represented using a network graph. To enhance the model's rationality, they incorporated operational precedence constraints. Given the complexity of the problem, they proposed a hybrid NSGA-II method to minimize both carbon emissions and machining costs.

Fu, et al. [15] addressed a real-world challenge by estimating the annual daily traffic and transport emissions for a nationwide road network. They applied a linear association to model the relationship between carbon costs and the distances traveled by vehicles. While, Xiao-Hong, et al. [16] presented a low-carbon and environmentally protective perspective. To solve the model, they described a hybrid genetic algorithm with heuristic criteria, using a real-world case to verify its effectiveness. The simulation results illustrate the model's application. Finally, they introduced the concept of carbon pricing and explore its potential impact on carbon emissions and overall costs, showing that the carbon pricing strategy effectively reduces carbon dioxide emissions within cold-chain logistics networks. Peng, et al. [17] introduced a memetic approach to solve the Green Vehicle Routing Problem (GVRP). Their solution embraces the green concept by utilizing electric vehicles, which have limited driving ranges and require recharging during operation. To manage various neighborhood moves, they incorporated an adaptive local search strategy in their approach, inspired by the reinforcement learning method and based on a reward-punishment mechanism.

Jiang, et al. [18] proposed a Traveling Salesman Problem that focuses on reducing carbon emissions in last-mile delivery. The objective of the proposed problem is to minimize both total costs and carbon emissions by strategically allocating parcel lockers and optimizing delivery routes. The research of Al-Zubaidi, et al. [19] addressed an environmentally friendly delivery-pickup problem for Home Hemodialysis Machines (HHMs), which are regarded as limited commodities. It presents a bi-objective mixed-integer linear programming model aimed at minimizing both the total system cost and overall carbon emissions. The problem is solved using the Torabi and Hassini (TH) technique, and for medium- and large-scale instances, a multi-objective meta-heuristic algorithm, called the self-learning non-dominated sorting genetic algorithm (SNSGA-II), is developed to find efficient solutions. Obi, et al. [20] proposed a genetic algorithm approach to determine the optimal distance. The tournament selection process aimed to achieve the best possible result, guiding the algorithm toward the optimal value of the fitness function. In their experiments, the optimization outcome was influenced by two key factors: the number of iterations and the population size of the algorithm.

Aurachman [21] introduced the city-TSP; it is a variant of TSP that considers urban constraints, goals, and parameters. One of the things that was considered was the noise level emitted by a truck. Dutta, et al. [22] presented a bi-objective model for the Green Vehicle Routing Problem (G-VRP) that addresses the issue of Greenhouse Gas (GHG) emissions. The model also considers demand as a rough variable. To solve the proposed model, the researchers employed the Non-Dominated Sorting Genetic Algorithm II (NSGA-II). Finally, the optimal solution from the Pareto front is selected using the Multicriteria Optimization and Compromise Solution method (VIKOR, the acronym in Serbian). HadjTaieb, et al. [23] formulated a mixed integer linear programming model, the authors proposed a bi-objective GVRPTW-TD-2MS (Green Vehicle Routing Problem with Time Windows, Time-Dependent, and Two-Stage Multi-Skilled) model. This model aims to minimize overall carbon emissions from vehicles during the caregivers' tours, while maximizing the total negative visitor preferences. The approach considers green time windows, synchronization, aspect restrictions, precedence constraints, disjunction constraints, and incorporates various frameworks and the diverse skills of caregivers.

Mugion, et al. [24] aimed to simulate the stochastic multi-objective green vehicle routing problem (GVRP), which simultaneously addresses economic, environmental, and social goals. The study introduced a novel hybrid search technique that effectively resolved the VRP. This approach was then applied to solve the stochastic multi-objective GVRP, revealing trade-offs between the three objectives through Pareto fronts. Additionally, the paper presented the impact of extending customer time windows on the overall results. Bajaj and Dhodiya [25] addressed the green multiple Traveling Salesman Problem (mTSP) by using a proposed Reference Point Aspiration Level-based Multi-Objective Quasi Oppositional Jaya (RPAL-based MOQO Jaya) algorithm. In this green mTSP, multiple salesmen are tasked with traveling under risk and carbon emission constraints, with all salesmen required to return to the depot (starting city). The problem is modeled using two approaches: Expected Value and Optimistic Value models, considering the uncertainties in travel cost, time risk, and carbon emissions. The green mTSP focuses on minimizing risk and carbon emissions, treating them as constraints in the problem.

2.2. Public Transportation and CO2 Emission Reductions

Numerous studies have investigated sustainable transportation systems and public transportation. In this section, we will highlight some key studies that contribute to the understanding of sustainable transportation and its impact on reducing carbon emissions, improving efficiency, and enhancing urban mobility. Taniguchi, et al. [26] presented a correlation between the urban forms of 67 cities and their annual per-capita petroleum consumption. Makido, et al. [27] explored the relationship between CO2 emissions and urban form across six sectors in 50 cities. The authors found that compact urban forms generally lead to lower CO2 emissions from passenger transportation compared to sprawling cities. They used the Tokyo Metropolitan Area and Kagawa Prefecture as case studies to represent metropolitan and regional areas, respectively.

The goal of the paper by Dey, et al. [28] was to assess how much the fleet of public transportation buses could reduce emissions by using alternative fuels. The outcomes demonstrated that each scenario offers a notable decrease in emission levels. Mugion, et al. [24] investigated urban public transportation systems that promote sustainable behaviors, such as opting for carpooling, bike sharing, and carsharing instead of private vehicle ownership. However, their research was not based on real-world data. The goal of Al-Zubaidi, et al. [19] was to manage the public bus transportation system by applying scientific planning approaches such operating networks to achieve maximum passenger flow and apply the minimum path approach to determine the shortest path. Three elements were considered in the greatest number of passengers, the shortest travel time, and the minimal carbon dioxide emissions. In their study Leichter, et al. [29] was carried out in Brazil to ascertain the anticipated environmental impact of the public bus transportation system based on various scenarios. This has led to the definition of the present and future environmental profiles, taking into account a case study of the public transportation system in Porto Alegre.

The goal of the Palmer [30] paper is to propose a strategy for decarbonizing Portugal's bus fleet by replacing the current, fossil fuel-fueled fleet with an entirely electric fleet in a period of fourteen years. The study demonstrates that, given that every vehicle will be replaced when it reaches the age of 14, it is feasible to replace the entire fleet of Portuguese urban buses with electric vehicles. The study of Pradhan, et al. [31] then looked at the relationship between usage frequency and trip-based CO2 emissions from private transportation modes as well as the relationship between usage frequency and rail and bus service evaluation overall. This study also investigated whether differences in the evaluation of the "hard" and "soft" qualities of public transportation services are related to emissions. Hassouna [32] study aimed to assess the projected sustainability of the public bus sector in Westbank, Palestine, by developing prediction models for the number of buses and passenger cars. The study evaluated the potential sustainability of the sector if it expands and the number of buses increases to meet global minimum standards. Although extensive research has been conducted globally on the sustainability of public transportation systems and their environmental impacts, no comprehensive study has specifically focused on this issue in Tunisia. Therefore, the aim of this study is to evaluate the sustainability of Tunisia's public transportation system and determine the significance of its environmental effects

From the literature review, it is evident that researchers who have considered the environmental aspect in their studies have suggested multi-objective models. Solving the MOTSP using an exact algorithm is highly challenging. To address this, we present the DM4-PMO, a novel two-phase metaheuristic designed for solving the bi-objective TSP. The details of this approach will be discussed in the following section.

3. The Novel Dhouib-Matrix-4 Metaheuristic and its Application Method for Determining the CO_2 Emissions

A new metaheuristic namely Dhouib-Matrix-4 (DM4) is developed by the first author in Dhouib [5] to solve the mono objective (distance) Travelling Salesmen Problem. Then adapted to increase the performance of a Computer Numerical Control Machine in Dhouib and Pezer [33] and Dhouib [34] enhanced for Wireless Sensor Networks in Dhouib [35] and performed for multi-objective in Dhouib [36].

In this manuscript, the novel Dhouib-Matrix-4 (DM4) is enhanced to reduce the CO2 emissions with trajectory distance. The enhanced method, namely DM4-PMO, works (see Figure 2) based on two phases (i) a preliminary Pareto non dominated solutions are generated using a modified weighted function (ii) a second Pareto not dominated frontier is created using a hierarchical resolution. Indeed, DM4-PMO is a multi-start metaheuristic where the constructive Dhouib-Matrix-TSP1 (DM-TSP1) heuristic is executed with several statistical metrics to create different good initial solutions. These solutions will be intensified by the novel local search technique Far-to-Near (FtN).

Algorithm of Dhouib-Matrix-4-PMO (DM4-PMO)

```
Input: Distance matrix, Sum metric
Output: Pareto2 set (list of non dominated solutions)
List-Metrics {Min, Max, Range, Mean, Sum, Q3, StDev, ...}
Set N_Start Len (List-Metrics)
w1 = 1, w2 = 0
Step = (1/N_Start)
#***Phase 1***
Repeat
    s1 = Dhouib-Matrix-TSP1 (DM-TSP1, w1, w2, List-Metrics[Cmpt])
    Far-to-Near (s1, w1, w2, List-Metrics[Cmpt])
    w1 := w1 – Step
    w2 := w2 + Step
Until termination condition met (Cmpt <= N_Start)
Generate Pareto1 set
#***Phase 2***
P_Step_size = Len(Pareto1) / N_Start
P_Number = 0
f1_before_f2 = True
Repeat
    Non_dominate = Select the element at the position P_Number from Pareto1 set
    Far-to-Near (Non_dominate, f1_before_f2)
    P_Number = P_Number + P_Step_size
    modify f1_before_f2
Until termination condition met (Cmpt <= N_Start)
Generate Pareto2 set
Return Pareto2
```

Figure 2.
The pseudo-code of the proposed DM4-PMO method.

Basically, the concept of Dhouib-Matrix was developed by the first author in order to solve combinatorial problems such the minimum Spanning Tree Problem in Dhouib [37] and the Shortest Path Problem in Dhouib, et al. [38]; Dhouib, et al. [39]; Dhouib [40] and Dhouib and Pezer [41].

4. The Tunisian Real World Case Study

It is well established that transportation activities have a significant negative impact on the environment, contributing to problems such as noise, pollution, and traffic congestion. The land transport sector is one of the largest contributors to CO_2 emissions within the transport industry. [42]. In this particular situation, Road transportation is a major contributor to air pollution, significantly affecting human health, especially in densely populated urban areas with heavy vehicle traffic. Furthermore, urban transportation plays a vital role in ensuring the smooth functioning of cities, addressing residents' communication needs, facilitating trade, and enhancing societal development. In the last two decades, the rapid growth of urban areas has led to a consistent rise in demand for public transportation systems, especially high-capacity modes such as buses [43].

Let us consider the case study of Tunisian public transportation (Bus). Table 1 gathers several data (The latitude, longitude, number of populations with Altitude) about twenty-four cities in Tunisia. Here, two criteria are minimized: the distance (*d*) and the emission of carbon dioxide (*CO2*).

$CO2 = dij * Tm * Aij$

Where

dij the Euclidian distance between city *i* and city *j*

Tm is the transportation mode (taken from Al-Zubaidi, et al. [19]), here the Tm

Aij is the altitude difference between city *i* and city *j*

Table 1.
The all-corresponding data for the twenty-four town in Tunisia.

Num	City	Latitude	Longitude	Population	Altitude
1	Tunis	36.806495	10.181532	602560	20
2	Sidi Bouzid	35.035439	9.483939	429912	359
3	Sfax	34.739822	10.760020	265131	147
4	Sousse	35.824503	10.634584	221530	66
5	Kairouan	35.671166	10.100547	186653	150
6	Kebili	33.707155	8.971462	163257	60
7	Gabès	33.888077	10.097522	116323	100
8	Ariana	36.866537	10.164723	114486	7
9	Gafsa	34.431140	8.775656	111170	293
10	Medenine	33.339922	10.495868	109409	33
11	Béja	36.733319	9.184368	109299	218
12	Kasserine	35.172272	8.830763	108794	643
13	Tataouine	32.921090	10.450896	95775	315
14	Monastir	35.764252	10.811288	93306	60
15	Ben Arous	36.743500	10.231976	88322	74
16	Mahdia	35.502446	11.045721	79545	82
17	El Kef	36.167965	8.709579	73706	615
18	Nabeul	36.451289	10.735663	73128	153
19	Manouba	36.809328	10.086327	58792	118
20	Bizerte	37.276758	9.864161	46700	33
21	Jendouba	36.507226	8.775656	46459	215
22	Tozeur	33.918534	8.122933	37365	36
23	Siliana	36.088721	9.364534	31251	815
24	Zaghouan	36.409119	10.142317	20387	530

The environment is hazardously affected by transportation. The most alarming thing is the CO2 emissions. Complex calculations are needed to estimate fuel consumption and CO2 emissions from mobile sources, and because some variables, like driving style, weather, traffic, and the like are difficult to quantify, the results can only be approximated. In our research, we rely on the methodology for calculating the environmental impact of carbon (see Table 2), as outlined in the foundational article by [19].

Table 2.
The carbon dioxide emission by only one passenger, kilometer and type.

Type	Consumption	Type	Consumption
Foot/Bicycles/animal	0	Medium car	0.133
Motorcycle	0.094	Big car	0.183
Electric car	0.043	Bus	0.064
Small car	0.11	Mini bus	0.055

The DM4-PMO generates two Pareto non-dominated solutions. The first Pareto list is generated based on a dynamic modification of criteria weighs: Figure 3.a illustrates the (254075) realizable solutions and Figure 3.b shows their correspondent (24) Pareto non dominated solutions.

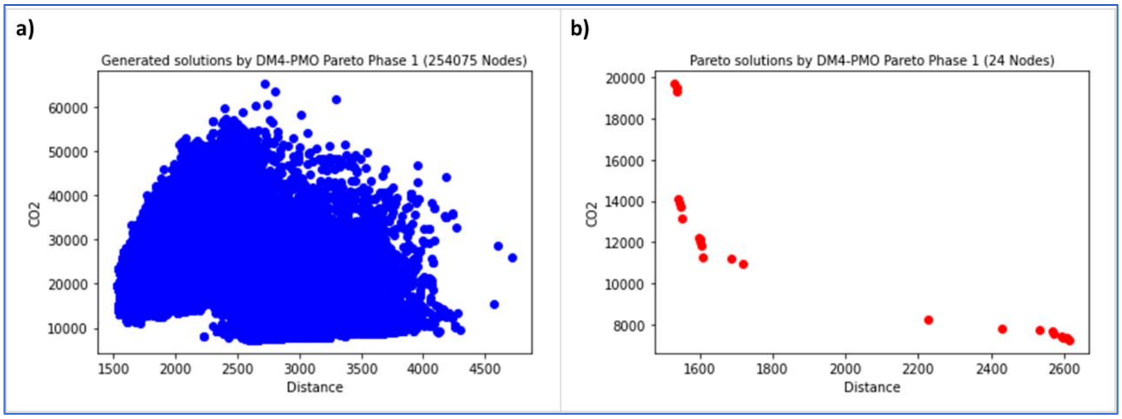

Figure 3.
The results generated by DM4-PMO after the first phase.

The second Pareto list is created using switched hierarchical function (it represents an improvement of the first Pareto set): Figure 4.a depicts the (803955) visited solutions and Figure 4.b shows their correspondent (35) Pareto non dominated solutions.

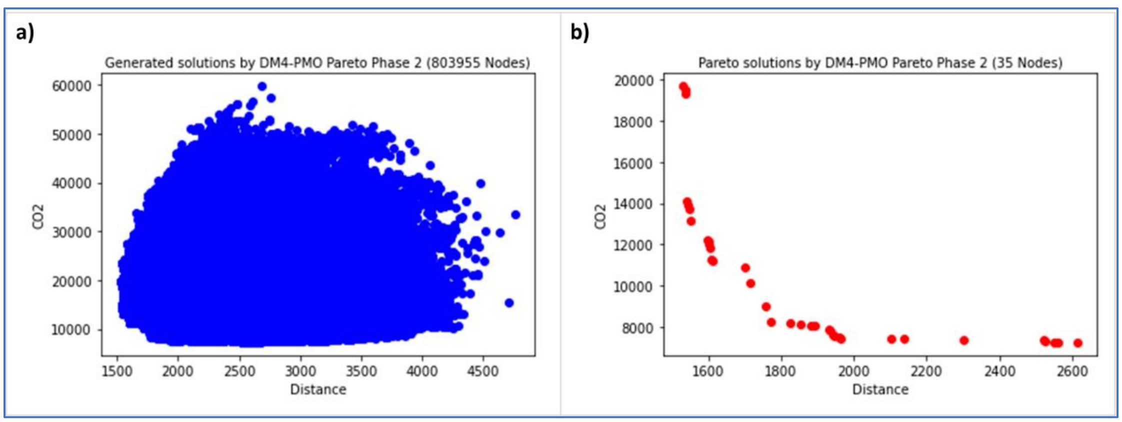

Figure 4.
The results generated by DM4-PMO after the second phase.

The DM4-PMO is repeated ten iterations and all the generated Pareto non-dominated set solutions are gathered and represented in Figure 5.

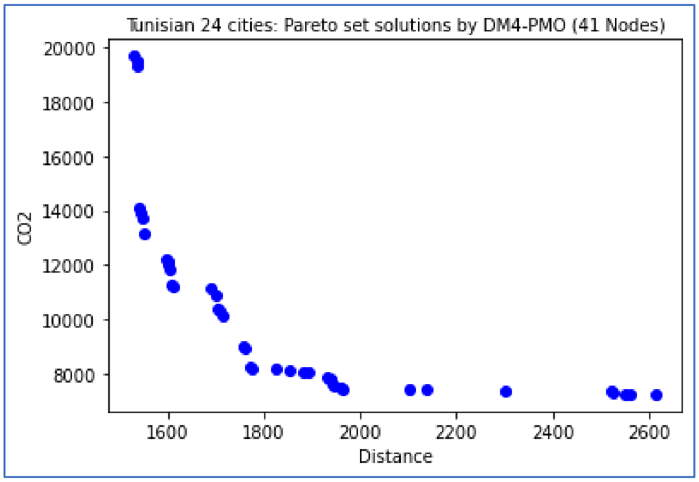

Figure 5.
The Pareto of non-dominated solutions after ten iterations.

5. Conclusion

Transport plays a crucial role in driving economic growth but also has a significant negative impact on the environment. Transport planning studies are becoming increasingly essential for developing large-scale solutions to address the escalating challenges of urban transportation. This study investigated the impact of public transport services on travel-related CO_2 emissions. The Dhouib-Matrix-4 (DM4), a novel metaheuristic, is introduced in this paper to tackle the sustainable Traveling Salesman Problem within a multi-objective framework. This variation of the classic TSP incorporates additional factors related to fuel consumption and the resulting emissions (with the conventional minimization of the distance). Consequently, minimizing fuel consumption that reduce the CO_2 emissions is considered as crucial to determine the shortest possible route. Furthermore, the strategy outlined here to suggest an urban bus fleet with low emissions can be applied in different situations to help businesses become more environmentally friendly. As a perspective to this work, the proposed DM4-PMO metaheuristic will be studied for other multi-objective problems such as the financial portfolio problem.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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