9th INTERNATIONAL CONFERENCE
”TOWARDS A HUMANE CITY“
Reshaping Mobility
Novi Sad 19th and 20th October 2023

Dragan Simić[1]
E-mail: dsimic@uns.ac.rs
Vladimir Ilin[1]
E-mail: v.ilin@uns.ac.rs
[1] Faculty of Technical Sciences in Novi Sad
Trg Dositeja Obradovića 6, 21000 Novi Sad

THE ANALYSIS OF ELECTRIC VEHICLE APPLICATIONS IN TRAVELLING SALESMAN PROBLEM

Keywords

Electric vehicles
Transportation logistics
Unmanned aerial vehicle
Battery recuperation
Metaheuristics

Abstract

Many corporate policies aim to promote transportation modes with lower emissions of pollution and greenhouse gases. Travelling salesman problem (TSP) is among the most well-studied optimization problems in operations research. The solution of the TSP by exact solutions, heuristics solutions, and approximation algorithms can be applied. Rather than focus on finding the most effective route, TSP is often concerned with finding the cheapest solution. Electric vehicles (EVs) are an emerging alternative to internal combustion engines. Recently technical and technological implementation of TSP extends classical TSP which in general presents electric travelling salesman problem (ETSP), which applications present hybrid solutions of: (i) drones cooperate with classical trucks; (ii) drones cooperate with electric trucks, and (iii) drones operate on their own. The capacity of electric vehicle (EV) battery in TSP; (ii) hybrid simulated models the electric TSP; and (iii) deploying EV and unmanned aerial vehicles as extension of TSP are analised in this study.

1. INTRODUCTION

Transport is the backbone of the European economy, accounting for about 7% of the gross domestic product (GDP) due to the fact that transport industry offers over 5% of total employment in the European Union (EU). As a network industry, transport requires elements such as infrastructures, vehicles, equipment, information and communication technology (ICT) applications and operational procedures to interact smoothly in order to move people and goods efficiently. Public revenues also benefit from transportation: 0.6% of the GDP is collected from vehicle taxes; and the greatest part of energy taxes, that counts 1.9% of the GDP, comes from taxes on fuel [1].

In the environmental aspects, transportation has been the sector with the largest growth rate of greenhouse gas (GHG) emissions compared to 1990. Moreover, road transport caused 39,000 deaths in EU in 2008. 60% of the global oil consumption and 25% of energy consumption are due to transportation [1]. 69% of road accidents occur in cities, and 25% of the CO_2 emission of the whole transport sector comes from urban transport [2]. Therefore, one can easily understand the importance of transportation in urban areas for private individuals, public authorities and enterprises.

The rest of the paper is organized in the following way: Section 2 overviews the last of travelling salesman problem. Section 3 presents mathematical formulation of basic TSP model. The analysis of electric vehicle applications in the following aspects: (i) minimising capacity of electric vehicle (EV) battery in TSP; (ii) hybrid simulated models the electric TSP; and (iii) deploying EV and unmanned aerial vehicles as extension of TSP are presented in Section 4. Finally, Section 5 provides concluding remarks and some points for future works.

2. THE LAST OF TRAVELLING SALESMAN PROBLEM

The traveling salesman problem (TSP) is an algorithmic problem tasked with finding the shortest route between a set of points (nodes) and locations that must be visited. It was first described by Irish mathematician Sir William Rowan Hamilton (1805–1865) and British mathematician Thomas Penyngton Kirkman (1806–1895) in the 1800s through the creation of a game that was solvable by finding a Hamilton cycle, which is a non-overlapping path between all nodes. After about one century, the Austrian mathematician Karl Menger (1902–1985) invited the research community to consider from a mathematical point of view the following problem taken from the everyday life. A travelling salesman has to visit exactly once each one of a list of cities and then return to the home city. It is known the cost of traveling from any city to next other city. It is known the cost of travelling from any city to next other city, and the point of interesting is the tour of least possible cost the salesman can take. Therefore, TSP is actually one of the most significant problems in the history of applied mathematics, since the TSP is NP-hard (nondeterministic polynomial time) problem. But on the other side TSP's problems are wide applicability, such as: school bus routes, home service calls problems.

TSP has been studied for decades and several solutions have been theorized. The simplest solution is to try all possibilities, but this is also the most time consuming, expensive, and not efficient method. On the other hand, many solutions use heuristics, which provides probability outcomes: *nearest neighbor*, *the Greedy heuristic*, *insertion heuristics*, *Christofides algorithm* [1]. However, the results are approximate and not always optimal. Once a tour has been generated by some tour construction heuristic, the solution could be improved. There are several ways to do this, but the most common ones are the 2-opt, 3-opt, and finally *k*-opt local searches.

Their performances are somewhat linked to the construction heuristic used [2]. Other solutions include branch and bound [3], Monte Carlo [4], and Las Vegas algorithms [5], and some other simple applications of the TSP [6].

However, since the TSP is NP-hard, it will be very time consuming to solve larger instances with guaranteed optimality. Rather than focus on finding the most effective route, TSP is often concerned with finding the cheapest solution. In TSPs, the large number of variables creates a challenge when finding the shortest route, which makes approximate, fast and cheap solutions all the more attractive, used by wide area of metaheuristics algorithms: ant colony optimisation [7], tabu search algorithm [8], particle swarm optimization [9], firefly algorithm [10].

3. MATHEMATICAL FORMULATION OF TRAVELING SALESMAN PROBLEM

Like any other mathematical problems, it is necessary to translate the TSP into its mathematical description. Many literatures had attempts this but one the easiest to understand is in [11] where TSP is described as follows:

"The TSP can be defined on a complete undirected graph G = (V, E) when it is symmetric or on a directed graph G = (V, A) if it is asymmetric. The set $V = \{1, \dots, n\}$ is the vertex set, $E = \{ i, j : i, j \in V, i < j\}$ is an edge set and $A = \{ i, j : i, j \in V, i \neq j\}$ is an arc set. A cost matrix $C = (c_{ij})$ is defined on E or on A. The most matrix satisfies the triangle inequality whenever $c_{ij} \leq c_{ik} + c_{kj}$" for all i, j, k. In particular, this case planar problems for which the vertices are points $Pi = (Xi, Yi)$ in the plane, and c_{ij} is the Euclidean distance. The triangle inequality is also satisfied if c_{ij} is the length of a shortest path from i to j on G." Some of the literatures calculated the cost (distance), c_{ij} using Manhattan distance or geometric distance instead of Euclidean distance.

4. ELECTRIC VEHICLES AND TRAVELING SALESMAN PROBLEM

There are many different TSP scientific researches and also the applications applied in industry and transportation. Effort has been devoted to the solution of the TSP by exact solutions, heuristics solutions, and approximation algorithms which can be applied. On the scientific-practical point of view, TSP is not a solitary example of NP-hard transportation problem. The *vehicle routing problem* (VRP) constitutes a generalization of the TSP that consists of determining the shortest circuit or cycle passing through each of *n* cities only once. However, from a practical point of view, VRPs are in general much more difficult to solve than TSPs of the same size. The most algorithms for the VRP are heuristics, reflecting the relative difficulty of the problem. The *last-mile delivery* has witnessed an enormous increase in quality demand in a continuously growing market, especially due to the rapid spread of distribution, online shopping platforms, e-commerce, and in general in e-business.

On the other hand, recently technical and technological implementation of TSP extends classical TSP which in general presents electric travelling salesman problem (ETSP), which applications present hybrid solutions of: (i) drones cooperate with classical trucks; (ii) drones cooperate with electric trucks, and (iii) drones operate on their own.

4.1. Minimising capacity of electric vehicle battery in TSP

The energy in a hybrid vehicle is one of the things that have been paid attention to, one of which can be seen from the research on optimal energy regulation for each process [12]. There is research that tries to optimise the electric vehicle route by considering the charging station [13]. However, so far it is not easy succeed in finding research that tries to find the optimal route with the assumption that charging stations are present at each destination.

Various public transportations can start using electric power sources. However, there are battery capacity constraints. When the distance is too far, the battery capacity is not sufficient to provide the required power. In the research paper [14], is explained how the bottleneck TSP is applied to minimize battery capacity requirements. So that vehicles can choose the right route by minimizing the maximum distance between destinations. The optimization process is carried out with the Brute Force algorithm in python programming language.

Due to the limited battery capacity of EVs and the fixed locations of stationary charging stations (SCs), EVs typically require additional travel distance to be charged via SCs, Wireless charging (WC) allows EVs to recharge while traveling, potentially reducing travel distance, consumed time, and land use. This problem is formulated as a mixed integer programming model in which the travel speeds on Wireless charging locations (WCLs) are considered as multiple given options. The algorithm is used, to solve small-scale instances to optimality and heuristics for larger instances [14].

4.2. Hybrid simulated annealing and tabu search method for the ETSP

The electric travelling salesman problem with time windows (ETSPTW) is an extension of the well-known TSP with time windows (TSPTW) is presented in study [15]. The ETSPTW additionally considers recharging operations of the electric vehicle at identical charging stations. However, different charging technologies used at public or private stations result in different charging times of the electric vehicles. Therefore, that study extends the ETSPTW by additionally considering charging operations at customer locations with different charging rates, called hereafter the electric travelling salesman problem with time windows and mixed charging rates (ETSPTW-MCR). That study is the first which considers both private and public charging stations for the ETSPTW. In addition to the extended version of the ETSPTW, the paper introduces a new and effective hybrid simulated cooperation of annealing and tabu search (SA/TS) algorithms to solve the ETSPTW-MCR problem efficiently. Distinct from the existing hybridization of SA and TS, the proposed hybrid SA/TS algorithm employs efficient search procedures based on the TSPTW restrictions, a modified solution acceptance criterion, and an advanced tabu list structure.

4.3. Electric vehicle and unmanned aerial vehicles in extended TSP

Last mile delivery includes the activities necessary for the customer to obtain the goods purchased, and these activities are typical for urban areas, city centres, home deliveries, and rural logistics regions. The idea of deploying electric vehicle and unmanned aerial vehicles (UAV), also known as drones, to perform "last-mile" delivery in logistics operations has attracted increasing attention in the past few years. In this paper, an electric vehicle TSP with drone (EVTSPD) is formulated as a mixed integer linear program, in the research paper [16]. Logistic organizations with a new method of delivering parcels which can extend the driving range of both vehicles and decrease the operation cost.

There are several challenges in EVTSPL: the vehicle driving range limitations, the existence of charging's station that can possibly be visited multiple times or not at all, and planning the UAV's route alongside that of the EV, introduce major complications to the problem. In the previous research which did not include electricity constraints, report a solution time of about 3 hours to solve a network containing 10 nodes, using a commercial solver [17]. Thus, heuristics designed for EVTSPD are necessary to solve a problem with practical size. An iterative three-step decomposition heuristic algorithm is presented [16]. The heuristic algorithm decomposes the problem into three sub-problems: (i) electric vehicle path construction; (ii) UAV node insertion; and (iii) final solution feasibility check. There are a variety of different combinations of electric vehicle node and UAV node, an iterative approach is used to improve the final result and record the best-known solution.

The research paper [18], is proposed solution and an algorithm based on a combination of the combinatorial optimisation algorithm which includes genetic algorithm (GA). This algorithm solves the truck drone in tandem team or last mile effort for TSP problem for parcel delivery operations. The aim of this approach is to minimise total last mile delivery cost. Each truck carries a drone which is launched from a stop to deliver a parcel within range to a nearby stop while operating in parallel with the truck. The truck and drone work in parallel operations to deliver packages. Therefore, the search optimisation problem is divided in two sub-problems: (1) first, it is being optimised for the truck routing; (2) and second, it is being optimised for the drone routing. The drone is constrained with its range (fly distance) and speed. An operation is when a truck launches the drone, truck and drone deliver to separate locations, and the truck then recovers the drone at a rendezvous location for battery swaps and loading. The main idea is to determine a route for truck and drone, as well as operations, whose cost function minimises total time which is calculated from minimum total last mile delivery cost. Total time is based on the times for the operations (launch – deliver – recover). The maximum time of an operation for truck or drone is used to calculate total time for the route.

5. CONCLUSION AND FUTURE WORK

In recent years, a growing number of logistics companies have introduced electric vehicle or unmanned aerial vehicles in the delivery operations and solve TSP and its extension in typical for urban areas and city logistics. The aim of this paper is to analyses electric vehicle applications based on TSP, and its extension such as last mile delivery. Recently, as is shown there are many challenges in different fields on applications for solving NP-hard TSP. Unfortunately, this paper cannot mention *all* possible problems which could be found in previous and also recently research papers.

There are so many challenges for the researchers in travelling salesman problem, last-mile delivery, vehicle routing problem and all their extensions. On the other side applications: (i) individually electrical vehicle application; (ii) classical truck and drone; (iii) electrical truck in tandem with drone; and/or (iv) singly electrical drone applications; are open fields for all researchers in relatively new field.

ACKNOWLEDGMENT

This research has been supported by the Ministry of Science, Technological Development and Innovation through project no. 451-03-47/2023-01/200156 "Innovative scientific and artistic research from the FTS (activity) domain".

REFERENCES

[1] Nilsson, C. "Heuristics for the traveling salesman problem", Technical report, Linköping University, Sweden, 2003.

[2] Rego C., Gamboa D., Glover F., Osterman C., "Traveling salesman problem heuristics: Leading methods, implementations and latest advances", *European Journal of Operational Research*, vol. 211, pp. 427–441, 2011.

[3] Grymin R., Jagiello S., "Fast Branch and Bound Algorithm for the Travelling Salesman Problem", 15th IFIP International Conference on Computer Information Systems and Industrial Management. pp. 206-217 2016.

[4] Ming L.F., *Markov Chain Monte Carlo and the Traveling Salesman Problem* , Master of Philosophy in Statistics, The Chinese University of Hong Kong, Graduate School 1995.

[5] Li K., "Solving the traveling salesman problem using efficient randomized parallel approximation algorithms", *Parallel Algorithms and Applications*, vol. 10, issue 3-4, pp. 271-281, 1997.

[6] Lenstra J.K., Kan R., "Some simple applications of the travelling salesman problem", *Journal of the Operational Research Society*, vol. 26, issue 4, pp. 717–733, 1975.

[7] Wang Y., Han Z., “Ant colony optimization for traveling salesman problem based on parameters optimization”, *Applied Soft Computing*, vol. 107, 107439, 2021.

[8] Gangadevi E., “Implementing tabu search on traveling salesman problem”, *International Journal of Advance Research in Science and Engineering*, vol. 07, pp. 857-863, 2018.

[9] Wang K-P., Huang L., Zhou C-G.; Pang W., “Particle swarm optimization for traveling salesman problem, Proceedings of the International Conference on Machine Learning and Cybernetics, 2003.

[10] Jati G.K., Suyanto M.R., *Discrete firefly algorithm for traveling salesman problem: A new movement scheme*. Swarm Intelligence and Bio-Inspired Computation, pp. 295-312, Elsevier, 2013.

[11] Matai R., Singh S., Mittal M.L., *Traveling Salesman Problem: an Overview of Applications, Formulations, and Solution Approaches*, *Traveling Salesman Problem*, *Theory and Applications*. InTech, 2010.

[12] Jiménez-Espadafor F.J., Guerrero D.P., Trujillo E.C., García M.T., Wideberg J., “Fully optimized energy management for propulsion, thermal cooling and auxiliaries of a serial hybrid electric vehicle”, *Applied Thermal Engineering*, vol. 91, pp. 694-705, 2015. Pages 694-705

[13] Alesiani, F., Maslekar, N., “Optimization of charging stops for fleet of electric vehicles: A genetic approach”, *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 3, pp. 10-21, 2014.

[14] Aurachman R., Saraswari D.P., “Minimizing capacity of electric vehicle battery using bottleneck traveling salesman problem”, *Journal of Physics* vol. 1811, 012068 (2021)

[15] Zhu T., Boyles S.D., Unnikrishnan A., “Electric vehicle traveling salesman problem with drone with fixed-time-full-charge policy, arXiv:2201.07992 [math.OC] April 2022.

[16] Küçükoğlu İ., Reginald D., Cattrysse D., “Hybrid simulated annealing and tabu search method for the electric travelling salesman problem with time windows and mixed charging rates”. *Expert Systems with Applications*, vol. 134, pp. 279-303, 2019.

[17] Yurek, E.E., Ozmutlu, H.C. “A decomposition-based iterative optimization algorithm for traveling salesman problem with drone”, *Transportation Research Part C: Emerging Technologies*, vol. 91, pp. 249-262, 2018.

[18] Simić, D., Calvo-Rolle, J.L., Villar, J.R., Ilin, V., Simić, S.D., Simić, S., *An Approach of Optimisation in Last Mile Delivery*. Lecture Notes in Networks and Systems, vol. 750, pp 311–320, Springer, Cham, 2023.