Traveling Repairmen Problem: A Biogeography-Based Optimization

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Abstract. Traveling Repairman Problem (TRP), which is also known by names cumulative traveling salesman problem, the deliveryman problem and the minimum latency problem, is a special variant of Traveling Salesman Problem (TSP). In contrast to the minimization of completion time objective of TSP, the desired objective of TRP is to minimize the cumulative latency (waiting time or delay time) of all customers. In this paper, a generalized version of TRP with multi depots and time windows, namely Multi Depot Traveling Repairman Problem with Time Windows (MDTRPTW) is considered. A group of homogeneous repairmen initiate and finish their visit tours at multiple depots. Each customer must be visited exactly by one repairman within their provided earliest end latest times. Being a challenging Nondeterministic Polynomial-hard (NP-hard) optimization problem, exact solution approaches are not expected to scale to realistic dimensions of MDTRPTW. Thus, we propose a biogeography-based optimization algorithm (BBOA) as a metaheuristic approach to solve large size MDTRPTW problems. The proposed metaheuristic is analyzed in terms of solution quality, coefficient of variation as well as computation time by solving some test problems adapted from the related literature. The efficacy of the proposed solution methodology is demonstrated by solving instances with 288 customers within seconds.

Keywords: Traveling salesman problem · Heuristic algorithms · Logistics problems · Routing

1 Introduction

Traveling Repairman Problem (TRP), which is also known as Delivery Man Problem [14], Minimum Latency Problem [5] or Cumulative Traveling Salesman Problem [4] is one of the special variants of the Traveling Salesman Problem (TSP) [1]. With the rapid growth in e-commerce and virtual markets due to the COVID-19 pandemic, customer satisfaction due to logistics activities has become more imperative than ever. The aim of TRP is to minimize the total latency (delay time) of all customers. The latency of a customer is defined as the time passed from the beginning of the travel until this customer's service

J. Xu et al. (Eds.): ICMSEM 2022, LNDECT 144, pp. 506–515, 2022.
https://doi.org/10.1007/978-3-031-10388-9_37

is completed. An important generalization of TRP is named as multi depot traveling repairman problem with time windows (MDTRPTW). There are k tours, each departs from and returns to the depot. Each customer must be visited exactly once within time window. This problem arises in various logistics problems ranging from the transportation of perishable items, cargo delivery and drug delivery from pharmaceuticals to pharmacies.

It is known that TRP is a Nondeterministic Polynomial-hard (NP-hard) challenging combinatorial optimization problem [1]. Therefore, exact solution approaches for TRP and its variants fail to handle realistic sized instances and the majority of the existing studies in the literature concentrate on heuristic approaches [2,6,15]. There are only two papers that present mathematical formulations for multi depot TRP (MDTRP) without considering time windows [12,19]. The first formulation for MDTRP is developed by Ruiz and Voß [12]. They solve only 3 problems with 10 nodes, 4 depots and 5 vehicles. When the problem size increases, to 25 nodes, their model fails to solve the problem within the given time limit. Therefore, they propose a Partial Optimization Metaheuristic under Special Intensification Conditions (POPMUSIC) algorithm to solve larger size problems. The second formulation for MDTRP is presented by Wang et al. [19] and they develop a local search algorithm as well. Moreover, there are several approximate methods for MDTRP in the literature. Besides the heuristic algorithms developed by Ruiz and Voß [12] and Wang et al. [19], the approximation algorithms are proposed by Chaudhuri et al. [7], Chekuri and Kumar [8], Post and Swamy [16] and Martin and Salavatipour [13]. None of these studies consider time windows.

The heuristic algorithms developed so far in the literature for MDTRP are based on a single solution and are not population based. As stated in Elshaer and Award [10], Genetic Algorithm (GA) is the most applied approach among the population-based algorithms for routing problems. In addition, Salehi and Masoumi [17] implement a hybrid Biogeography-based optimization algorithm (BBOA), which is a population-based algorithm for TSP. Also, Berghida and Boukra [3] develop a new enhanced BBOA for vehicle routing problem with heterogeneous fleet, mixed backhauls, and time windows. They show that, their algorithm outperforms those of particle swarm optimization and ant colony optimization.

The first mathematical formulations for MDTRPTW are proposed in [11]. In this paper, we propose a biogeography-based optimization algorithm to solve TRP. The performance of developed algorithm is examined in terms of solution quality, coefficient of variation and computation time by using some test problems in the literature. It is shown that the proposed metaheuristic approach finds good quality solutions for medium and large-size problems within seconds.

The rest of this study is organized as follows. In Sect. 2, the MDTRPTW is formally introduced. In Sect. 3, the structure of biogeography-based algorithm and implementation of the proposed metaheuristic algorithm on MDTRPTW are explained. In Sect. 4, the results of the computational analysis are reported. Conclusions and future research directions are provided in Sect. 5.

2 Problem Statement

Consider a directed graph $G = (V', A)$ where V is the set of customers, D is the set of depots, $V' = (D \cup V)$ is the set of nodes and $A = \{(i,j) : i,j \in V', i \neq j\}$ is the set of arcs. c_{ij} is the time of the travel from the node i to node j that can be symmetric ($c_{ij} = c_{ji}$) or asymmetric ($c_{ij} \neq c_{ji}$). m is the number of repairman located at each depot. a_i and b_i is the earliest and latest visiting time (time window) for the customer i respectively.

With those given aforementioned, we define MDTRPTW as:

- Each customer must be served once.
- Each repairman must depart from and return to the depot.
- Each customer must be visited within its time windows, (if the repairman arrives before the earliest visiting time it must wait).
- Waiting cost occurred due to early arrival (before its earliest visiting time) is not taken into account.
- The objective is to find a set of routes by minimizing the total latency for all customers.
- Service time of each customer is equal to zero.

3 Proposed Biogeography-Based Optimization Algorithm for the MDTRPTW

Biogeography-based optimization algorithm is a population-based metaheuristic approach introduced by Simon in 2008 [18]. BBOA differs from GA in that it does not involve reproduction process. Also, in BBOA features of the good solutions are used to improve the bad solutions but in genetic algorithm new solutions are produced by changing between random solutions with cross-over operator. The idea behind BBOA is natural migration of animals to find a habitat. Each habitat (H_i) represents a feasible candidate solution of the problem ($i = 1, ..., N$). Each habitat has a fitness value called as habitat suitability index (HSI) that shows the quality of the solution. In nature, some parameters like rainfall, crop diversity, temperature etc. are influencing the habitats. These features are named as the suitability index variables (SIV).

In BBOA, there are two main operators named as migration and mutation. The function of migration operator is to generate a new solution in each iteration by sharing information between habitats. Each habitat has an immigration and emigration rate. When an immigration rate increases, the habitat has a stronger tendency to take a solution feature by migration from another habitat. On the other hand, when an emigration rate increases, the habitat has a stronger tendency to give a solution feature by migration to another habitat. The quality of a solution (fitness) is analogous to HSI. A good solution (a habitat) with a high HSI value tending to share characteristics with a bad habitat to improve it.

A habitat with a high HSI value is analogous to a good solution, this habitat has a high emigration rate and low immigration rate. Similarly, a habitat with a low HSI value is analogous to a bad solution so, this habitat has a low emigration rate and high immigration rate. Thus, good solutions share characteristics with bad solutions in order to make them better and bad solutions accept the features of good solutions to improve their quality. This is analogous to the migration between habitats and determine the main structure of the BBOA. The immigration rate of the i^{th}habitat (λ_i) and the emigration rate of the ith habitat (μ_i) is calculated through Eq. (1) and Eq. (2) respectively.

$$\lambda_i = I\left(1 - \frac{k_i}{N}\right) \tag{1}$$

$$\mu_i = E\left(\frac{k_i}{N}\right) \tag{2}$$

where, k_i is the fitness rank of the i^{th} habitat and N is the population size. Firstly, habitats are sorted from the best to the worst according to their HSI values. For the habitat with the best HSI value, k is equal to N and for the habitat with the worst HSI value, k is equal to 1. The parameter I indicates the maximum rate of immigration and the parameter E is the maximum rate of emigration. These are user-defined parameters. The function of the mutation operator is to provide diversity in order to escape getting caught in the local optimal solutions. The mutation rate of the i^{th} habitat (m_i) is calculated with Eq. (3). $m_{\max}$ is the maximum mutation rate and it is a user-defined parameter. P_i denotes the probability of ith habitat calculated using Eq. (4) where v_i is calculated in Eq. (5).

$$m_i = m_{\max}\left(1 - \frac{P_i}{P_{\max}}\right) \tag{3}$$

$$P_i = \frac{v_i}{\sum\limits_{i=1}^{n} v_i} \tag{4}$$

$$v_i = \begin{cases} \frac{n!}{(n+1-i)!(i-1)!} i = 1, ..., i' \\ v_{n+2-i} i = i' + 1, ..., n+1 \end{cases} \quad i' \geq \frac{n+1}{2} \tag{5}$$

In the following, the structure of the proposed BBOA for MDTRPTW is described by considering the solution representation, generation of the initial solution, calculating the fitness value and the steps of the proposed BBOA.

3.1 Solution Representation

The first step for a heuristic algorithm is solution representation. It has an effect on the quality of results so, it is important to use an appropriate data structure in the algorithm. We use a permutation encoding representation including the routes of each depot for MDTRPTW. Each array provides a candidate solution. As an example, consider a problem with 15 customers, 3 depots where each depot has 2 repairmen. The dimension of a candidate solution array for this example is $(3 \times 2) + 15 = 21$. One such exemplary solution representation is depicted in Fig. 1.

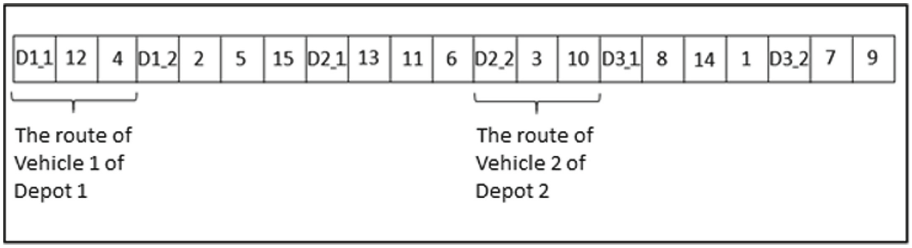

Fig. 1. Illustration of solution representation

The next step of the algorithm is to generate initial population.

3.2 Initial Population

Initial solutions are used to start the search mechanism in heuristic algorithms. There are two common approaches to generate an initial solution for initial population. One is random generation and the second is to use specific construction heuristics for the considered problem. In this paper, we generate the initial population randomly for the MDTRPTW. The solutions that do not meet the problem constraints are rejected.

3.3 Calculating the Fitness Value

A fitness value of each habitat (HSI) in the initial population is computed after its generation. The objective function of MDTRPTW corresponds to fitness function so, in this problem, the fitness function is the total time passed until all customers are served. HSI values are easily calculated according to fitness function given in Eq. (6) where s_i denotes time passed until visiting customer i. If the repairman arrives at the customer before its earliest visiting time, the customer's service time is taken as the customer's earliest visiting time. If the repairman arrives at the customer between its earliest and latest visiting time, the customer's service time is taken as the arrival time of the repairman.

$$HSI = \sum_{i \in V} S_i \tag{6}$$

3.4 Proposed BBOA for MDTRPTW

The overall procedure of the proposed BBOA for the MDTRPTW is outlined in Algorithm 1 depicted in Fig. 2. The parameter set of BBOA which affect the performance of the algorithm is determined experimentally. BBOA starts by first initializing the population consisting of habitats. Then, at each iteration, HSI values of habitats are calculated. Secondly, habitats are sorted according to their HSI values and the immigration rate (λ_i), emigration rate (μ_i) and mutation rate

(m_i) are evaluated for each one. The migration and mutation process, which are the main operators of BBOA are applied respectively considering feasible solutions. When the algorithm is terminated, the best solution found throughput the algorithm is reported as the solution for MDTRPTW.

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Algorithm 1 Pseudo-code of BBOA for the MDTRPTW
Input: MDTRPTW Data, BBO Parameters
Output: Best Solution
Set the initial parameters of the algorithm
Initialize randomly a population of N habitats
While Termination Criteria is not met do
   Calculate fitness (HSI) for each habitat
   Sort habitats according to HSI
   Calculate λ, μ and m for each habitat
   Use the migration operator
   Use the mutation operator
   Evaluate the HSI for each habitat
   Perform elitism and update the best solution
end while
return best solution
```

Fig. 2. The proposed BBOA

4 Computational Analysis

In this section, the results of the computational experiments are summarized. The proposed heuristic algorithm was coded using Python 3.6.2 programming language. All computational experiments were performed on a PC with Intel Core i7-3630QM CPU 2.40 GHz and 16 GB of RAM. The efficacy of the meta-heuristic solution approach is evaluated in terms of solution quality, coefficient of variation as well as computation time. Solution quality is evaluated according to percentage deviation from the best objective value (Dev%).

4.1 Test Problems

The test problems generated for multi depot vehicle routing problem with time windows by Cordeau et al. [9] are used to investigate the performance of proposed BBOA for the MDTRPTW problem. The test set consist of 15 problems (5 small, 5 medium and 5 large) with the number of customers varying from 20 to 288.

4.2 Computational Results

The performance of proposed BBOA is analyzed in terms of solution quality, coefficient of variation and computation time. Each instance is run 30 times by the proposed heuristic with different random seeds. Firstly, the results of the computational analysis according to the percentage deviation from the best objective value (Dev%) and coefficient of variation (CoV) for the problem set are given in Table 1.

In Table 1, the first 4 columns provide the problem name, the numbers of customers, depots and repairmen, respectively. The optimal value column shows the optimal results obtained by Uzun [11]. BBO average column displays the average values obtained from 30 replications. The last two columns represent the percentage deviation and coefficient of variation. It is seen that the optimum result is found in almost all of the small problems, the results are obtained with very small deviations as the problem size grows, and there are also results for the problems that cannot be obtained with the mathematical model.

We can say that the proposed algorithm has a high performance. Similar performance is also seen in Table 2, for the other performance criterion, namely, the computational time (CPU.)

Under CPU column for BBOA, we see the average computational times of solving 30 replications. From Table 2, it can be seen that maximum computational time is 172.88 s for the problem with 192 customers, 4 depots and 6 repairmen. The developed metaheuristic approach is able to solve problems with 288 customers under a minute.

Table 1. Performance analysis of BBOA in terms of solution quality

Problem	Customer	Depot	Repairmen	Optimal value	BBO average	Dev (%)	CoV
pr1	20	4	2	5322	5322	0	0
			1	5345	5345	0	0
pr2	30	4	2	8619	8619	0	0
			1	8793	8793	0	0
			3	8619	8619	0	0
pr3	96	4	3	25202	25202	0	0
			2	-*	26137.5	-	0.015
pr4	144	6	6	38051	38716.8	1.75	0.026
			4	38051	38796.7	1.96	0.031
			8	37018	37358.5	0.92	0.023
pr5	192	4	8	47284	47988.5	1.49	0.041
			6	-*	51035.6	-	0.062
pr6	288	4	18	77520	78426.9	1.17	0.049
			15	-*	82945.2	-	0.065
			12	-*	83567.1	-	0.071

Notes: ∗ Optimal solution cannot be found by mathematical model in time limit 7200 s

Table 2. Performance analysis of BBOA in terms of computational time

Problem	Customer	Depot	Repairmen	CPU	
				Mathematical model	BBO (average)
pr1	20	4	2	0.44	2.41
			1	0.3	2
pr2	30	4	2	11.16	4
			1	3.58	3.88
			3	0.36	3.8
pr3	96	4	3	343.08	12
			2	-	13.16
pr4	144	6	6	116.31	32.14
			4	497.36	27,3
			8	32.7	25.2
pr5	192	4	8	2393.22	123.1
			6	-	172.88
pr6	288	4	18	1948.05	27.89
			15	-	26.47
			12	-	115.36

5 Conclusion

In this paper, we consider a special variant of TRP called the multi depot traveling repairman problem with time windows (MDTRPTW). Important applications of this problem can be found in many real-life areas such as humanitarian logistics, emergency aid logistics, distribution of perishable goods, school bus routing, cargo delivery, drug delivery and similar problems. We propose a metaheuristic algorithm named as biogeography-based optimization algorithm (BBOA) to find near optimal solutions within a reasonable computational time for realistic sized dimensions. In order to explore the effectiveness of the proposed BBOA, we have conducted an experimental analysis by solving benchmark instances adapted from related literature. The efficacy of the metaheuristic approach is evaluated in terms of solution quality, coefficient of variation and computation time. The experimental results over 15 test instances reveal that the developed metaheuristic algorithm is able to solve problems with 288 customers under a minute. Also, the proposed metaheuristic algorithm represents a high performance when find good quality solutions within acceptable CPU times for large-size problems. For future research, the proposed heuristic approach can also be adapted to other variants of TRP. Developing hybrid metaheuristic algorithms by using BBOA and other approaches for MDTRPTW and other variants as TRP with multi depot, TRP with profits, and multi-objective TRP are other future research topics.

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