

SOLVING MIN-MAX CAPACITATED VEHICLE ROUTING PROBLEM BY LOCAL SEARCH

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Abstract. Vehicle routing is a class of combinatorial optimization problems in transportation and logistics. Min-max capacitated vehicle routing is a problem of this class in which the length of the longest route must be minimized. This paper investigates local search approach for solving the min-max capacitated vehicle routing problem with different neighborhood structures. We also propose a combined function instead of the objective function itself for controlling the local search. Experimental results on different datasets show the efficiency of our proposed algorithms compared to previous techniques.

Keywords. Vehicle routing, local search, min-max vehicle routing, combinatorial optimization.

1. INTRODUCTION

A large number of applications involve sets of clients that must be served by vehicles located at a common depot. Problems which optimize the selection of routes for the vehicles, are referred to as *vehicle routing problem* [27, 19]. Solving these problems is very hard and is still an active research topic which attracts the attention of many computer scientists due to their impact to the society and the economy. Many variants of vehicle routing applications have been studied in the literature, for example, Capacitated Vehicle Routing problem (CVRP) [32], Min-Max Vehicle Routing Problem (MMVRP) [1], Vehicle Routing Problem with Time Windows (VRPTW) [9], etc.

We consider in this paper the Min-Max Capacitated Vehicle Routing Problem (MM-CVRP). The goal of this problem is to ensure that all clients are served as soon as possible such that the total load of each vehicle does not exceed a predefined value. Due to the hardness of MMVRP, a simpler variant of this problem, MMCVRP is a NP-hard problem [2].

Figure 1 illustrates an example of MMCVRP with 3 clients 1, 2, 3 and the depot 0. The demand of each client is 2. There are two vehicles in which the capacity of each vehicle is 5. In this example, there are 6 solutions (see Figure 1). Among these 6 solutions, the best solution is the solution 2 (Figure 1b) with the objective 5.

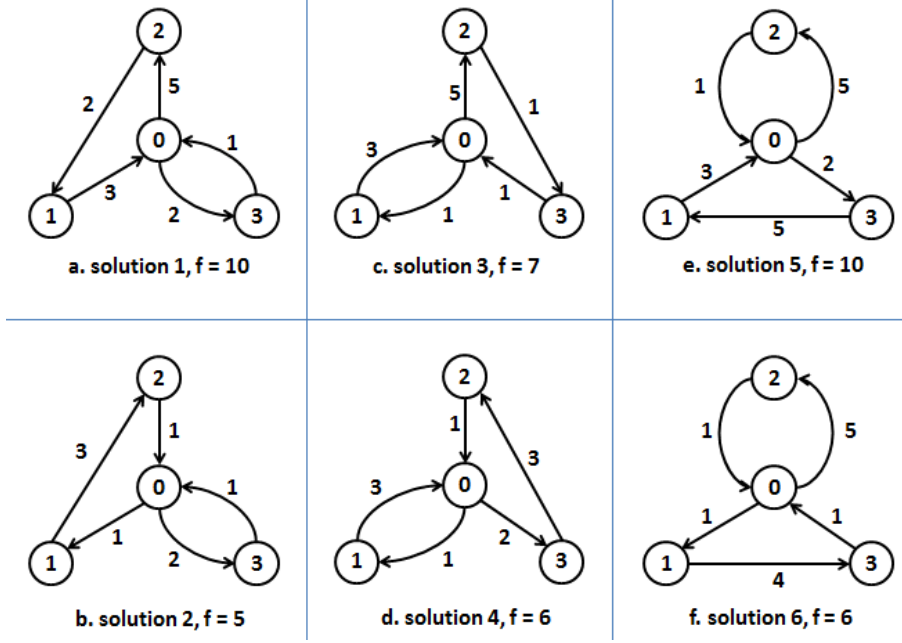


Figure 1. Illustrating example of MMCVRP

1.1. Problem formulation

This section describes the formulation of the min-max capacitated vehicle routing problem.

Input The input consists of following elements:

- N : number of client points
- $C = \{p_1, \dots, p_N\}$: client points
- K : number of vehicles
- s_i, t_i : starting and terminating points of vehicle i ($\forall i = 1, \dots, K$). In case all vehicles depart and return to the same depot, s_i, t_i refer to this physical depot
- c^i : the capacity of vehicle $i, \forall i = 1, \dots, K$
- $T = \{t_1, \dots, t_K\}$: set of terminating points of vehicles
- $B = \{s_1, \dots, s_K\}$: set of starting points of vehicles
- $D = B \cup T$: set of starting and terminating points of vehicles
- $V = C \cup D$: set of all points
- $c_{p,q}$: the distance from point p to point $q, \forall p, q \in V$

- d_p : the demand of client point p ($\forall p \in V$). $d_p = 0, \forall p \in D$ by convention.

Variables

- Decision variables x_p : the successor of point p in the solution. Domain of x_p is $V \setminus B$ ($\forall p \in V \setminus T$)
- Auxiliary variables l_p : represents accumulated demand on the route visiting point p from the starting point of this route until p ($\forall p \in V$).
- Auxiliary variables td_p : represents total distance on the route containing p from the starting point of this route to p ($\forall p \in V$)
- Auxiliary variables I_p : represents the index of route containing point p ($\forall p \in V$)
- Auxiliary variables f : represents the length of the longest path of the solution

Constraints

$$I_{s_i} = i, \forall i = 1, \dots, K \quad (1)$$

$$I_{t_i} = i, \forall i = 1, \dots, K \quad (2)$$

$$I_{x_p} = I_p, \forall p \in V \setminus T \quad (3)$$

$$l_{x_p} = l_p + d_p, \forall p \in V \setminus T \quad (4)$$

$$td_{x_p} = td_p + c_{p,x_p}, \forall p \in V \setminus T \quad (5)$$

$$l_{t_i} \leq c^i, \forall i = 1, \dots, K \quad (6)$$

$$f \geq td_{t_i}, \forall i = 1, \dots, K. \quad (7)$$

Constraints 1, 2 define the index of route containing starting and terminating points of this route. Constraint 3 specifies that a point and its successor must be in the same route. Constraints 1, 2, and 3 ensure that each client is serviced exactly once. Constraints 4 and 5 specify the relation between accumulated demand and distance of two consecutive points on the same route. Constraint 6 is the capacity constraint. Constraint 7 describes the objective function of the problem.

Objective function. The objective function to be minimized is f .

1.2. Related works

Dantzig and Ramser were the first scientists who introduce the ‘‘Truck Dispatching Problem’’ in [7], modelling how a fleet of homogeneous trucks could serve the demand for oil of a number of gas stations from a central hub and with a minimum travel distance. This became known as the ‘Vehicle Routing Problem’ (VRP), one of the most widely studied topics in the field of Operations Research. The study conducted by Eksioglu et al. in [12] revealed 1021 journal articles with VRP as the main topic, published between 1959 and 2008. The number

of solution methods introduced in the academic literature (for old as well as new variants of the VRP) has grown rapidly over the past decades. Moreover, the processing speed and memory capacity of current computers has increased significantly, enabling to solve larger instances of the VRP which spurs the progression in the research field and the development of commercial software for the VRP. According to a recent survey [22], thousands of companies, among others Coca-Cola Enterprises and Anheus-Bush Inbev, nowadays use VRP softwares.

CVRP differs from MMCVRP when its objective is to minimize the total length of routes. The practical importance of this problem leads to much motivation for the effort involved in the development of heuristic algorithms [16, 30] and exact algorithms [3, 14]. In [3], Baldacci et al. have described a branch-and-cut algorithm that is based on a two commodity network flow formulation of the CVRP. The algorithm proposed in [14] is very consistent on solving instances from the literature with up to 135 customers. For the latest research on CVRP, we refer to the researches [30, 4, 24, 34, 29].

VRPTW is an extension of CVRP when it considers additionally time window constraints that the clients must be served within predefined time windows. The most interest meta-heuristics used to solve the VRPTW are Tabu search (TS), genetic algorithm (GA), evolutionary algorithms (EA) and ant colony optimisation algorithm (ACO) [26]. Meta-heuristic controls local search processes, such as tabu search [5, 11], simulated annealing [6], genetic algorithms [31], Meta-heuristics controlling a subordinate construction heuristic, such as the greedy randomized search procedure (GRASP) proposed by [25], the RNET meta-heuristic [28] and multiple ant colony systems as proposed by [15]. [21] proposed an exact algorithm for the multiple vehicle routing problem with time windows.

Vehicle Routing Problem with Pick-up and Delivery (VRPPD), which models a real-life problem, is much more complicated than the classical VRP. The problem arises in practice when items need to be transported from the depot to customers and also need to be picked up at customers and brought back to the depot. There are many works that focus on solving this problem, for example in [17] the authors proposed a neighborhood search heuristics to optimize the planned routes of vehicles.

The min-max vehicle routing problem without capacity constraint (MMVRP) have been considered in the literature. Applegate et al. [1] proposed a branch and cut algorithm for solving this problem. Incomplete algorithms have also been proposed, for instance, approximation algorithm [2], neighborhood search algorithms [8, 13, 23], a genetic algorithm [33]. For the min-max capacitate vehicle routing problem (MMCVRP), Golden et al. proposed an algorithm [18] which consists of four distinct steps: initial CVRP solutions, generation of new CVRP solutions, recombination of CVRP solutions, and generation of MMCVRP solutions. Most recently, authors of [10] proposed a local search algorithm for solving MMCVRP using 2 kinds of neighborhoods: one-point move and cross-exchange move which will be detailed later.

In this paper, we propose a local search algorithm for solving MMCVRP. Our algorithm exploits various neighborhood structures proposed in the literature. Moreover, we propose to use a combined function for controlling the search instead of the objective function itself. This combined function will be shown to be efficient in the experiments. The paper is organized as follows. Section 2 describes the proposed local search algorithm. Section 3

presents the experiments. Section 4 concludes that paper and draws some future works.

2. PROPOSED LOCAL SEARCH ALGORITHMS

We describe in this section the proposed local search algorithm for solving MMCVRP. We start by presenting different neighborhoods proposed in the literature.

2.1. Neighborhoods

The neighborhoods we consider in our algorithm are described in [20] including one-point-move, two-point-move, two-opt-move, or-opt-move neighborhood, three-opt-move, three-point-move, cross-exchange neighborhoods. Due to lack of space, we do not present in detail these neighborhoods. Interested readers can refer to [20] for more detail about these neighborhood structures.

2.2. Local search algorithms

Before describing the local search algorithm, we propose a combined function that will be used as the quality function for controlling the search and which is described below.

2.2.1. Quality function

One of the core of a local search algorithm is a function F that models the quality of solutions. This function is also used to control the local search. Basically, F is the objective function itself, i.e., the length of the longest route among K routes of the solution. In this paper, we propose to combine in a lexicographic order the objective function and the total length of K routes into the control function F . The motivation for this combined function is explained as follows. The solution consists of K routes in which there might be several routes having the same longest length. A local move on a solution may change only one or two routes, thus cannot reduce the lengths of all longest routes of the solution. In this situation, the objective function cannot differentiate neighbors and the current solution (the presence of a plateau). By combining the objective function and the sum of lengths of K routes to establish the control function F , a best local move with respect to F may keep the objective function unchanged but reduce the total length of K routes (the number of longest routes may reduce). This bring opportunity to reduce the objective function in subsequent best local moves. As the min-max vehicle routing problem has a constraint on the capacity of vehicles, the satisfaction of this constraint must be prioritized most. To this end, the control function F consists of three components in a lexicographic order: the violations of the capacity constraint, the original objective function and the sum of lengths of K routes.

Formally, given a solution $s = \{r_1, \dots, r_K\}$ to the min-max vehicle routing problem which consists K routes r_1, \dots, r_K , we denote

- $td(r_i)$ the length of route r_i
- $l(r_i)$ the total demand of clients on route r_i

- $f(s) = \max_{i=1,\dots,K}\{td(r_i)\}$ the objective function of the problem
- $v(r_i) = \max\{0, l(r_i) - c^i\}$ the violations of the capacity constraint related to route r_i
- $v(s) = \sum_{i=1}^K v(r_i)$ the violations of the capacity constraint
- $t(s) = \sum_{i=1}^K td(r_i)$ the total length of the solution
- $F(s) = \langle v(s), f(s), t(s) \rangle$ the quality function.

The function F is treated in a lexicographic order: given two solutions s_1 and s_2 , we denote $F(s_1) < F(s_2)$ if:

- $v(s_1) < v(s_2)$ or
- $v(s_1) = v(s_2)$ and $f(s_1) < f(s_2)$ or
- $v(s_1) = v(s_2)$ and $f(s_1) = f(s_2)$ and $t(s_1) < t(s_2)$.

2.2.2. Local search

The proposed local search is depicted in Algorithm 1. It receives \mathcal{C} as a set of client points, s_i and t_i are the starting and terminating points of the route of vehicle i ($\forall i = 1, \dots, K$), \mathcal{L} is a list of considered neighborhoods, and a control function F that measures the quality of solutions. The initial solution is generated in line 1 which will be detailed in Algorithm 2. Line 2 updates the best solution found so far s^* . At each iteration of the local search, line 5 shuffles that order of the neighborhoods of \mathcal{L} . Lines 8–13 iteratively explore these neighborhoods. Each neighborhood exploration (see Algorithm 3 for more detail) will return a set of selected neighbors S which have the same quality evaluation e . The neighborhood exploration will terminate whenever it discovers a first neighbor which is better than the current solution s (lines 10–12). Line 14 replaces the current solution by a randomly selected neighbor of S . If the selected neighbor is better than the best solution found so far s^* , then s^* is updated (lines 15–16). Otherwise, the search augment the number of consecutive iterations nic in which no improvement is found by 1. The search will be restarted if nic exceeds a given parameters $maxStable$ (see lines 20–23).

Algorithm 2 depicts the method for generating an initial solution. The initial solution is generated in a greedy constructive manner. The algorithm receives a set of starting and terminating points (s_i, t_i) of K routes ($\forall i = 1, \dots, K$), a set \mathcal{C} of client points, a control function F that measures the quality of solutions, and returns a set of K routes visiting all clients \mathcal{C} . The algorithm initializes K routes without any client points (lines 2–4) and iteratively inserts greedily a selected client point to one of the K routes. $Cand$ records the most potential candidates, each candidate is represented by a pair of two points $\langle p, q \rangle$ (p will be inserted right after point q in the current solution). Lines 10–11 scan all candidates $\langle p, q \rangle$ in which S is the set of client points having not been in the solution and R is the set of points in the solution after which we can insert other client points. Line 12 computes a new solution s' by inserting p right after q in the current solution s . If the quality of s' is better than the best evaluation e^* , then all candidates in $Cand$ will be replaced by the new

candidate $\langle p, q \rangle$ (lines 13–15). Otherwise, if the quality of s' is equal to the best evaluation e^* , then this candidate will be added into $Cand$ (lines 17–19). Lines 23–26 select randomly a candidate from $Cand$ for the insertion and update S, R .

Algorithm 3 depicts a procedure that explores a given neighborhood. The procedure receives a neighborhood N and a set S of potential solutions which have been already found so far (i.e., by exploring previous neighborhoods), and returns a new set of best solutions and their evaluation. It scans all solutions of the considered neighborhood N and keeps track of the set of best solution with respect to the function F .

Algorithm 1. LSMMCVRP($((s_1, t_1), \dots, (s_K, t_K)), \mathcal{C}, \mathcal{L}, F$)

Input:

- $(s_1, t_1), \dots, (s_K, t_K)$ in which s_i and t_i are the starting and terminating points of the route of vehicle i
- \mathcal{C} : set of client points
- \mathcal{L} : list of neighborhoods
- Control Function F that measures the quality of solutions

Output: Set of K routes

```

1  $s \leftarrow \text{GenerateInitialSolution}((s_1, t_1), \dots, (s_K, t_K), \mathcal{C}, F)$ ;
2  $s^* \leftarrow s$ ;
3  $nic \leftarrow 1$ ;
4 while time limit is not expired do
5   |  $\text{Shuffle}(\mathcal{L})$ ;
6   |  $S \leftarrow \{\}$ ;
7   |  $e \leftarrow \infty$ ;
8   | foreach neighborhood  $N_i$  in  $\mathcal{L}$  do
9     |  $\langle S, e \rangle \leftarrow \text{Explore}(N_i, S, e)$ ;
10    | if  $e < F(s)$  then
11      | | BREAK;
12    | end
13  | end
14  |  $s \leftarrow \text{select}(S)$ ;
15  | if  $F(s) < F(s^*)$  then
16    | |  $s^* \leftarrow s$ ;
17    | |  $nic \leftarrow 1$ ;
18  | else
19    | |  $nic \leftarrow nic + 1$ ;
20    | | if  $nic > \text{maxStable}$  then
21      | | |  $s \leftarrow \text{GenerateInitialSolution}((s_1, t_1), \dots, (s_K, t_K), \mathcal{C}, F)$ ;
22      | | |  $nic \leftarrow 1$ ;
23    | | end
24  | end
25 end

```

Algorithm 2. GenerateInitialSolution($(s_1, t_1), \dots, (s_K, t_K), \mathcal{C}, F$)

Input: $(s_1, t_1), \dots, (s_K, t_K)$ in which s_i and t_i are the starting and terminating points (logical points) of the route of vehicle i . They refer to the same physical depot of the given problem

Output: set of K routes

```

1  $S \leftarrow \mathcal{C}$ ;
2  $R \leftarrow \{s_1, \dots, s_K\}$ ;
3 foreach do
4    $r_i \leftarrow \langle s_i, t_i \rangle$ ;
5 end
6  $s \leftarrow \{r_1, \dots, r_K\}$ ;
7 while  $S \neq \emptyset$  do
8    $Cand \leftarrow \{\}$ ;
9    $e^* \leftarrow \infty$ ;
10  foreach  $p \in S$  do
11    foreach  $q \in R$  do
12       $s' \leftarrow \text{AddOnePoint}(s, p, q)$ ;
13      if  $F(s') < e^*$  then
14         $Cand \leftarrow \{\langle p, q \rangle\}$ ;
15         $e^* \leftarrow F(s')$ ;
16      else
17        if  $F(s') = e^*$  then
18           $Cand \leftarrow Cand \cup \{\langle p, q \rangle\}$ ;
19        end
20      end
21    end
22  end
23   $\langle p^*, q^* \rangle \leftarrow \text{select}(Cand)$ ;
24   $s \leftarrow \text{AddOnePoint}(s, p^*, q^*)$ ;
25   $S \leftarrow S \setminus \{p^*\}$ ;
26   $R \leftarrow R \cup \{p^*\}$ ;
27 end
28 return  $s$ ;

```


Algorithm 3. Explore(N, S, e)

Input:

- N : a neighborhood
- S : set of solutions collected by exploring other neighborhoods so far
- e : evaluation of solutions in S

Output: S : set of new solutions and an evaluation e

```

1 for  $s_i \in N$  do
2   if  $F(s_i) < e$  then
3      $S \leftarrow \{s_i\}$ ;
4      $e \leftarrow F(s_i)$ ;
5   else
6     if  $F(s_i) = e$  then
7        $S \leftarrow S \cup \{s_i\}$ 
8     end
9   end
10 end
11 return  $\langle S, e \rangle$ ;

```

3. EXPERIMENTS

Table 1. Comparison between $N2$ and $NMCF$ on Christophides instances

| Instances | $N2$ | | | | $NMCF$ | | | | ρ |
|----------------|---------------|--------|--------|------------|---------------|--------|---------------|------------|--------|
| | min | max | avg | avg.t (s.) | min | max | avg | avg.t (s.) | |
| E-n7-k2.vrp | 54.00 | 54.00 | 54.00 | 0.00 | 54.00 | 54.00 | 54.00 | 0.00 | 0.00 |
| E-n13-k4.vrp | 74.00 | 74.00 | 74.00 | 0.32 | 74.00 | 74.00 | 74.00 | 1.44 | 0.00 |
| E-n22-k4.vrp | 110.00 | 110.00 | 110.00 | 2.03 | 110.00 | 110.00 | 110.00 | 3.62 | 0.00 |
| E-n23-k3.vrp | 242.00 | 244.00 | 243.90 | 7.11 | 243.00 | 244.00 | 243.45 | 27.35 | 0.18 |
| E-n30-k4.vrp | 164.00 | 164.00 | 164.00 | 2.97 | 164.00 | 164.00 | 164.00 | 2.17 | 0.00 |
| E-n30-k3.vrp | 192.00 | 206.00 | 201.30 | 10.42 | 191.00 | 195.00 | 192.45 | 10.85 | 4.40 |
| E-n31-k7.vrp | 75.00 | 83.00 | 80.10 | 20.66 | 71.00 | 80.00 | 74.00 | 47.03 | 7.62 |
| E-n33-k4.vrp | 244.00 | 245.00 | 244.50 | 19.99 | 244.00 | 244.00 | 244.00 | 11.07 | 0.20 |
| E-n51-k5.vrp | 113.00 | 121.00 | 117.35 | 78.74 | 112.00 | 115.00 | 113.50 | 67.07 | 3.28 |
| E-n76-k14.vrp | 97.00 | 112.00 | 106.00 | 100.05 | 90.00 | 99.00 | 93.60 | 27.22 | 11.70 |
| E-n76-k8.vrp | 108.00 | 129.00 | 117.70 | 86.16 | 99.00 | 102.00 | 100.05 | 94.57 | 15.00 |
| E-n76-k15.vrp | 90.00 | 96.00 | 93.65 | 129.15 | 88.00 | 90.00 | 88.95 | 61.48 | 5.02 |
| E-n76-k10.vrp | 103.00 | 122.00 | 114.75 | 92.96 | 95.00 | 106.00 | 99.55 | 31.69 | 13.25 |
| E-n76-k7.vrp | 107.00 | 129.00 | 118.20 | 118.01 | 105.00 | 110.00 | 107.35 | 120.49 | 9.18 |
| E-n101-k8.vrp | 127.00 | 151.00 | 135.15 | 157.97 | 112.00 | 121.00 | 117.05 | 69.01 | 13.39 |
| E-n101-k14.vrp | 105.00 | 116.00 | 111.40 | 140.71 | 100.00 | 104.00 | 101.50 | 68.04 | 8.89 |

In this section, we conduct two experiments. The first experiment is to compare our proposed algorithm and the local search algorithm of [10], the most recently algorithm for the min-max capacitated vehicle routing problem. The algorithm in [10] employed only

Table 2. Comparison between $N2$ and $NMCF$ on Kelly instances

| Instances | $N2$ | | | | $NMCF$ | | | | ρ |
|-------------|---------|---------|---------|------------|----------------|---------|----------------|------------|--------|
| | min | max | avg | avg_t (s.) | min | max | avg | avg_t (s.) | |
| kelly01.txt | 640.89 | 689.71 | 653.59 | 290.74 | 600.40 | 619.66 | 610.41 | 235.60 | 6.61 |
| kelly02.txt | 940.04 | 1226.85 | 1006.36 | 314.57 | 906.66 | 952.29 | 932.30 | 266.47 | 7.36 |
| kelly03.txt | 1239.52 | 1468.87 | 1301.62 | 319.30 | 1180.32 | 1318.84 | 1236.44 | 286.28 | 5.01 |
| kelly04.txt | 1348.06 | 1668.09 | 1429.13 | 358.81 | 1301.00 | 1471.14 | 1363.11 | 289.77 | 4.62 |
| kelly05.txt | 1442.22 | 1706.96 | 1545.20 | 274.69 | 1297.90 | 1431.05 | 1380.09 | 151.72 | 10.69 |
| kelly06.txt | 1176.22 | 1308.42 | 1234.17 | 302.15 | 1130.31 | 1179.30 | 1147.70 | 277.44 | 7.01 |
| kelly07.txt | 1288.99 | 1455.00 | 1334.43 | 319.11 | 1206.89 | 1291.04 | 1259.42 | 275.13 | 5.62 |
| kelly08.txt | 1232.39 | 1463.07 | 1287.31 | 329.25 | 1183.47 | 1292.61 | 1227.33 | 272.61 | 4.66 |
| kelly09.txt | 60.66 | 76.85 | 63.68 | 269.75 | 60.00 | 60.62 | 60.07 | 186.05 | 5.67 |
| kelly10.txt | 69.63 | 82.63 | 74.58 | 305.01 | 68.00 | 69.16 | 68.38 | 244.31 | 8.31 |
| kelly11.txt | 81.00 | 102.87 | 87.24 | 303.64 | 76.00 | 77.60 | 76.23 | 260.75 | 12.63 |
| kelly12.txt | 97.13 | 112.36 | 104.37 | 318.97 | 88.67 | 99.34 | 94.70 | 274.65 | 9.27 |
| kelly13.txt | 43.40 | 53.30 | 46.20 | 187.26 | 43.07 | 44.61 | 43.39 | 155.64 | 6.08 |
| kelly14.txt | 51.06 | 74.80 | 55.60 | 273.18 | 49.82 | 51.98 | 50.93 | 281.93 | 8.41 |
| kelly15.txt | 57.98 | 65.67 | 62.20 | 276.39 | 56.65 | 60.84 | 58.02 | 290.87 | 6.71 |
| kelly16.txt | 67.87 | 78.92 | 70.14 | 300.09 | 63.30 | 72.00 | 66.68 | 290.42 | 4.93 |
| kelly17.txt | 41.41 | 65.67 | 46.93 | 248.71 | 39.96 | 42.26 | 40.59 | 250.15 | 13.51 |
| kelly18.txt | 51.24 | 92.15 | 64.98 | 212.32 | 49.37 | 51.39 | 50.08 | 259.05 | 22.93 |
| kelly19.txt | 65.76 | 113.89 | 71.42 | 282.77 | 61.89 | 65.70 | 63.63 | 288.53 | 10.91 |
| kelly20.txt | 77.15 | 96.36 | 81.78 | 187.64 | 76.40 | 79.66 | 77.50 | 288.20 | 5.24 |

Table 3. Comparison between NM and $NMCF$ on Christophides instances

| Instances | NM | | | | $NMCF$ | | | | ρ |
|----------------|---------------|--------|---------------|------------|---------------|--------|---------------|------------|--------|
| | min | max | avg | avg_t (s.) | min | max | avg | avg_t (s.) | |
| E-n7-k2.vrp | 54.00 | 54.00 | 54.00 | 0.00 | 54.00 | 54.00 | 54.00 | 0.00 | 0.00 |
| E-n13-k4.vrp | 74.00 | 74.00 | 74.00 | 0.31 | 74.00 | 74.00 | 74.00 | 1.44 | 0.00 |
| E-n22-k4.vrp | 110.00 | 110.00 | 110.00 | 4.98 | 110.00 | 110.00 | 110.00 | 3.62 | 0.00 |
| E-n23-k3.vrp | 242.00 | 243.00 | 242.10 | 20.50 | 243.00 | 244.00 | 243.45 | 27.35 | -0.56 |
| E-n30-k4.vrp | 164.00 | 164.00 | 164.00 | 5.55 | 164.00 | 164.00 | 164.00 | 2.17 | 0.00 |
| E-n30-k3.vrp | 191.00 | 197.00 | 192.95 | 53.72 | 191.00 | 195.00 | 192.45 | 10.85 | 0.26 |
| E-n31-k7.vrp | 70.00 | 82.00 | 77.55 | 81.80 | 71.00 | 80.00 | 74.00 | 47.03 | 4.58 |
| E-n33-k4.vrp | 244.00 | 245.00 | 244.15 | 85.87 | 244.00 | 244.00 | 244.00 | 11.07 | 0.06 |
| E-n51-k5.vrp | 114.00 | 121.00 | 118.70 | 119.50 | 112.00 | 115.00 | 113.50 | 67.07 | 4.38 |
| E-n76-k14.vrp | 103.00 | 118.00 | 111.10 | 146.64 | 90.00 | 99.00 | 93.60 | 27.22 | 15.75 |
| E-n76-k8.vrp | 110.00 | 126.00 | 118.85 | 140.44 | 99.00 | 102.00 | 100.05 | 94.57 | 15.82 |
| E-n76-k15.vrp | 91.00 | 98.00 | 94.45 | 155.69 | 88.00 | 90.00 | 88.95 | 61.48 | 5.82 |
| E-n76-k10.vrp | 106.00 | 125.00 | 117.40 | 149.21 | 95.00 | 106.00 | 99.55 | 31.69 | 15.20 |
| E-n76-k7.vrp | 113.00 | 127.00 | 119.35 | 115.85 | 105.00 | 110.00 | 107.35 | 120.49 | 10.05 |
| E-n101-k8.vrp | 130.00 | 156.00 | 141.65 | 140.07 | 112.00 | 121.00 | 117.05 | 69.01 | 17.37 |
| E-n101-k14.vrp | 104.00 | 119.00 | 113.25 | 161.05 | 100.00 | 104.00 | 101.50 | 68.04 | 10.38 |

two neighborhood structures: one-point move and cross-exchange move and did not use the combined control function. We denote $N2$ this algorithm. Our proposed algorithm exploits multiple neighborhoods and uses a combined control function. We denote $NMCF$ our proposed algorithm. All the algorithms have been implemented using the CBLSVR library of [10], a constraint-based local search library for general vehicle routing problems.

Table 4. Comparison between *NM* and *NMCF* on Kelly instances

| Instances | <i>NM</i> | | | | <i>NMCF</i> | | | | ρ |
|-------------|---------------|---------|----------------|------------|----------------|---------|----------------|------------|--------|
| | min | max | avg | avg_t (s.) | min | max | avg | avg_t (s.) | |
| kelly01.txt | 612.93 | 656.07 | 630.63 | 177.01 | 600.40 | 619.66 | 610.41 | 235.60 | 3.21 |
| kelly02.txt | 899.67 | 1041.15 | 949.12 | 265.01 | 906.66 | 952.29 | 932.30 | 266.47 | 1.77 |
| kelly03.txt | 1192.79 | 1317.13 | 1250.64 | 310.34 | 1180.32 | 1318.84 | 1236.44 | 286.28 | 1.14 |
| kelly04.txt | 1304.34 | 1531.80 | 1388.07 | 354.59 | 1301.00 | 1471.14 | 1363.11 | 289.77 | 1.80 |
| kelly05.txt | 1394.89 | 1592.97 | 1464.86 | 173.50 | 1297.90 | 1431.05 | 1380.09 | 151.72 | 5.79 |
| kelly06.txt | 1156.07 | 1273.24 | 1217.88 | 163.16 | 1130.31 | 1179.30 | 1147.70 | 277.44 | 5.76 |
| kelly07.txt | 1241.57 | 1304.21 | 1277.28 | 281.88 | 1206.89 | 1291.04 | 1259.42 | 275.13 | 1.40 |
| kelly08.txt | 1193.26 | 1331.25 | 1227.02 | 337.62 | 1183.47 | 1292.61 | 1227.33 | 272.61 | -0.03 |
| kelly09.txt | 60.65 | 65.22 | 62.04 | 168.89 | 60.00 | 60.62 | 60.07 | 186.05 | 3.18 |
| kelly10.txt | 69.09 | 72.65 | 70.49 | 247.25 | 68.00 | 69.16 | 68.38 | 244.31 | 3.00 |
| kelly11.txt | 77.11 | 80.02 | 78.70 | 310.37 | 76.00 | 77.60 | 76.23 | 260.75 | 3.14 |
| kelly12.txt | 88.99 | 101.09 | 94.43 | 320.92 | 88.67 | 99.34 | 94.70 | 274.65 | -0.28 |
| kelly13.txt | 43.08 | 51.75 | 47.48 | 102.21 | 43.07 | 44.61 | 43.39 | 155.64 | 8.61 |
| kelly14.txt | 50.04 | 57.68 | 53.02 | 211.42 | 49.82 | 51.98 | 50.93 | 281.93 | 3.94 |
| kelly15.txt | 56.17 | 65.18 | 59.33 | 238.13 | 56.65 | 60.84 | 58.02 | 290.87 | 2.20 |
| kelly16.txt | 63.76 | 71.94 | 66.76 | 255.37 | 63.30 | 72.00 | 66.68 | 290.42 | 0.12 |
| kelly17.txt | 41.48 | 65.67 | 45.64 | 126.34 | 39.96 | 42.26 | 40.59 | 250.15 | 11.06 |
| kelly18.txt | 50.71 | 92.15 | 69.20 | 123.83 | 49.37 | 51.39 | 50.08 | 259.05 | 27.63 |
| kelly19.txt | 62.69 | 84.50 | 64.63 | 238.43 | 61.89 | 65.70 | 63.63 | 288.53 | 1.54 |
| kelly20.txt | 76.29 | 96.36 | 79.70 | 121.05 | 76.40 | 79.66 | 77.50 | 288.20 | 2.76 |

Table 5. Comparison between Golden [18] and *NMCF* on Christophides, Mingozzi and Toth instances

| Instances | Golden[18] | | | | <i>NMCF</i> | | | | ρ |
|----------------|------------|-----|--------|------------|-------------|------------|--------|------------|--------|
| | min | max | avg | avg_t (s.) | min | max | avg | avg_t (s.) | |
| CMT-1-m5.txt | 194 | 225 | 212.15 | 150.1815 | 113 | 116 | 115.05 | 67.69775 | 45.77 |
| CMT-1-m6.txt | 155 | 186 | 170.69 | 151.461 | 103 | 103 | 103 | 2.65145 | 39.66 |
| CMT-1-m7.txt | 149 | 161 | 151.6 | 146.5 | 95 | 95 | 95 | 1.1177 | 37.34 |
| CMT-2-m10.txt | 125 | 128 | 125.34 | 135.371 | 95 | 109 | 100.95 | 12.32805 | 19.46 |
| CMT-2-m11.txt | 115 | 115 | 115 | 129.19 | 89 | 94 | 90.95 | 31.00855 | 20.91 |
| CMT-2-m12.txt | 113 | 113 | 113 | 125.191 | 88 | 93 | 89.95 | 17.3704 | 20.40 |
| CMT-3-m8.txt | 204 | 204 | 204 | 186.6735 | 116 | 124 | 119.75 | 19.8403 | 41.30 |
| CMT-3-m9.txt | 171 | 171 | 171 | 187.0545 | 107 | 115 | 111.1 | 34.3317 | 35.03 |
| CMT-3-m10.txt | 145 | 145 | 145 | 187.587 | 104 | 114 | 107.25 | 12.8914 | 26.03 |
| CMT-4-m12.txt | 168 | 168 | 168 | 396.2255 | 103 | 114 | 110.05 | 62.4103 | 34.49 |
| CMT-4-m13.txt | 139 | 139 | 139 | 390.7615 | 100 | 116 | 106.2 | 46.9419 | 23.60 |
| CMT-5-m16.txt | 130 | 130 | 130 | 732.64 | 108 | 145 | 121 | 189.4161 | 6.92 |
| CMT-5-m17.txt | 119 | 119 | 119 | 727.049 | 101 | 111 | 104.2 | 114.2479 | 12.44 |
| CMT-11-m7.txt | 229 | 229 | 229 | 242.2955 | 204 | 227 | 209.25 | 72.92035 | 8.62 |
| CMT-11-m8.txt | 219 | 219 | 219 | 242.2375 | 198 | 205 | 199.85 | 60.28815 | 8.74 |
| CMT-12-m10.txt | 127 | 127 | 127 | 187.2265 | 121 | 126 | 121.75 | 29.66425 | 4.13 |
| CMT-12-m11.txt | 124 | 124 | 124 | 186.9405 | 117 | 121 | 118.3 | 35.5866 | 4.60 |

Table 6. Comparison between Golden [18] and *NMCF* on Fisher instances

| Instances | Golden[18] | | | | <i>NMCF</i> | | | | ρ |
|---------------|------------|-----|-------|------------|-------------|-----------|--------|------------|--------|
| | min | max | avg | avg_t (s.) | min | max | avg | avg_t (s.) | |
| F-n72-m4.vrp | 98 | 104 | 99 | 118.756 | 66 | 68 | 67.75 | 59.95555 | 31.57 |
| F-n72-m5.vrp | 85 | 91 | 85.46 | 117.698 | 62 | 64 | 63.2 | 12.61015 | 26.05 |
| F-n72-m6.vrp | 67 | 67 | 67 | 118.4605 | 56 | 58 | 56.15 | 27.10635 | 16.19 |
| F-n135-m7.vrp | 293 | 293 | 293 | 302.084 | 299 | 309 | 300.8 | 74.22805 | -2.66 |
| F-n135-m8.vrp | 292 | 292 | 292 | 301.8725 | 295 | 299 | 296.65 | 49.4305 | -1.59 |

In the second experiment, we compare the performance of the *NMCF* algorithm and the algorithm proposed by Gold et al. in [18] on the instances described in that paper. In this comparison, we did not obtain exactly the same setting of instances that produced the results presented in [18]. Hence, we re-implemented the algorithm of Golden et al. [18] in Java programming language.

3.1. Instances and settings

The instances were taken from <http://neo.lcc.uma.es/vrp/vrp-instances/capacitated-vrp-instances/> with two data sets. The first data set is from Christofides and Eilon which consists 15 instances. The number of clients in this data set varies from 13 to 101. The second data set is from Golden, Wasil, Kelly and Chao which consists of 20 large-scale instances. The number of clients in this data set varies from 200 to 480.

The experiments were conducted on the machine Intel(R) Core(TM)i7-4790 CPU 3.60GHz with 16GB RAM. Each algorithm was executed 20 times for each instance with the time limit of 5 minutes.

3.2. Experimental results

The first experimental results are shown in Tables 1, 2, 3, 4. The structure of these tables are identical. Each table presents the results of two algorithms (the first algorithm is on the left and the second algorithm is on the right). For example, in Tables 1, 2, columns 2–5 present the minimum, maximum, average of the objective, and the average time to find best solution value among 20 executions of algorithm *N2*. Columns 6–9 presents the same information of algorithm *NMCF*. The last column of each table presents ρ , the percentage of improvement of the second algorithm compared to the first algorithm. More precisely, $\rho = \frac{f_1 - f_2}{f_1} \times 100$ in which f_1 and f_2 are respectively the average objective values of the first and the second algorithms in the table.

Experimental results show that in most of the cases, our proposed algorithm gives better results than *N2* in term of minimum, maximum, and average objective value among 20 executions for each instance. In the first data set (Christophides), among 320 executions, our proposed algorithm *NMCF* finds better solutions than the algorithm *N2* in 200 executions, while the algorithm *N2* finds better solutions in only 3 executions. In the second data set (Kelly), among 400 executions, our proposed algorithm *NMCF* finds better solution than *N2*

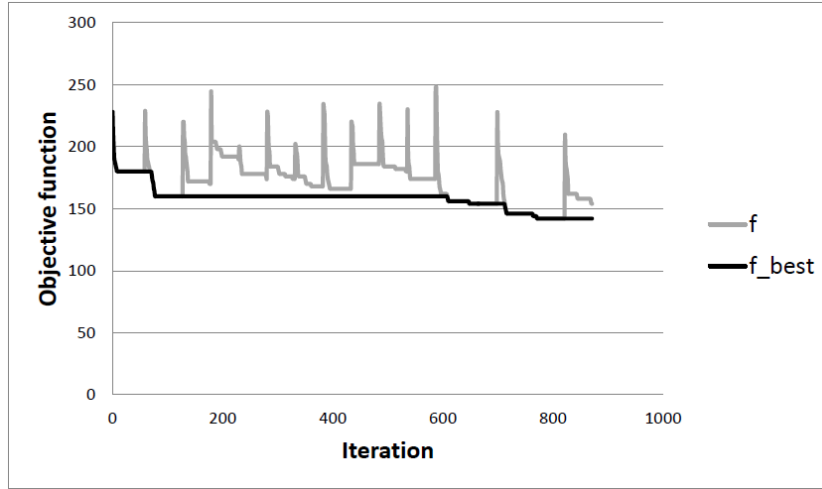
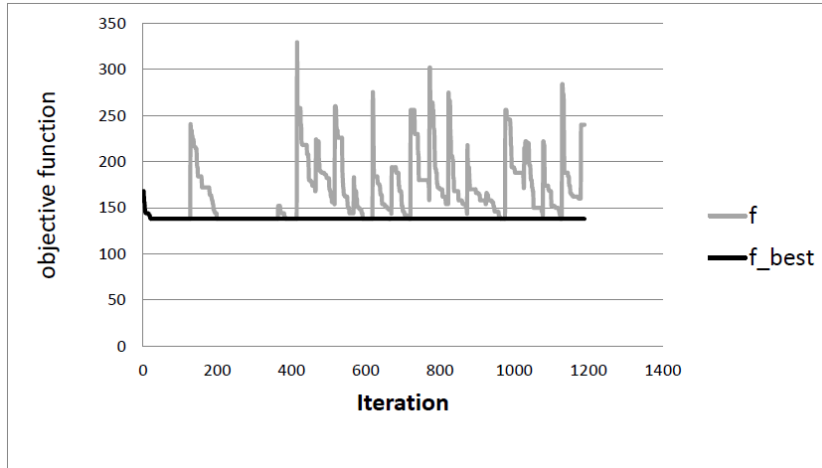
a. Algorithm $N2$ b. Algorithm $NMCF$

Figure 2. Evolution of the objective function found by $N2$ and $NMCF$ over iteration on the instance E-n101-k14.vrp

in 360 executions, while the algorithm $N2$ finds better solutions in only 20 executions.

To evaluate the efficiency of using combined control function, we compare our proposed algorithm $NMCF$ that uses a combined control function and the version that does not use combined control function (denoted by NM). The comparison is presented in Tables 3 and 4. The tables show that in most of the cases, the $NMCF$ algorithm finds better than NM .

Tables 5 and 6 compares the performance of our proposed algorithm $NMCF$ and the algorithm proposed by Golden et al. in [18] (denoted by Golden[18]). We observe that in term of average objective values, the $NMCF$ algorithm finds better result than those found by Golden[18] in most of the instances except that last two Fisher instances. However, the

improvement of Golden[18] compared to the *NMCF* algorithm is not significant.

Figures 2a and 2b present the behaviour of the two algorithms in an execution example. They plot the value of the objective function and the best objective function found by algorithms *N2* and *NMCF* over iterations on the instance E-n101-k14.vrp. We can see that the algorithm *NMCF* converges faster than the algorithm *N2*.

4. CONCLUSION

We considered in this paper the min-max capacitated vehicle routing problem and proposed a local search algorithm for solving it. The proposed local search algorithm exploits most of the neighborhood structures in the literature for vehicle routing problems. Experimental results on different data sets show that our proposed algorithm gives better results than the most recently algorithm. We also show the advantage of exploiting a combined control function during the search instead of using the objective function itself. Our future works focus on other metaheuristics search for solving the min-max capacitated vehicle routing problem, especially, we analyze and explore different neighborhoods in a dynamic way including removing ineffective neighborhoods.

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