A HYBRID ALGORITHM, BASED ON ITERATED LOCAL SEARCH AND GENIUS, FOR THE VEHICLE ROUTING PROBLEM WITH SIMULTANEOUS PICKUP AND DELIVERY

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ABSTRACT

This work deals with the Vehicle Routing Problem with Simultaneous Pickup and Delivery (VRPSPD). The VRPSPD is a common problem in the area of reverse logistics, which aims to plan the transportation of products to customers, as well as the return of leavings or products used by them for recycling or to special depots. The VRPSPD is NP-hard, since it can be reduced to the classical Vehicle Routing Problem when no client needs the pickup service. To solve it, we propose a hybrid heuristic algorithm, called GENILS, based on Iterated Local Search, Variable Neighborhood Descent and GENIUS. The proposed algorithm was tested on three well-known sets of instances found in literature and it was competitive with the best existing approaches. Among the 72 test-problems of these sets, the GENILS was capable to improve the result of 9 instances and to equal another 49.

1. INTRODUCTION

The Vehicle Routing Problem (VRP) was originally proposed by Dantzig and Ramser [7] and it can be defined as follows. Given a set of N clients, each one with a demand d_i, and a homogeneous vehicle fleet with capacity Q, the objective is to design the vehicle routes in such a way that the clients' demands are completely attended in a single visit and the sum of the traveled costs are minimized.

In the late 80's, Min [20] proposed an important variant of the VRP: the Vehicle Routing Problem with Simultaneous Pickup and Delivery (VRPSPD), in which the pickup and

delivery services must be performed simultaneously. This model is a basic problem in the field of Reverse Logistics. Its main goal is to manage the transportation of products to customers, as well as the return of residues or products utilized by these clients for recycling or specialized depots. The Reverse Logistic can be observed, for instance, in the postal logistics or in the distribution planning of the beverages industry.

The VRPSPD is a NP-hard problem since it can be reduced to the classical VRP when all clients do not need pickup services. Therefore, heuristic approaches have been frequently applied to solve the problem.

Min [20] proposed a three phase method for solving the distribution planning of a public library. The first phase consists in grouping the clients in clusters by means of the Average Linkage Method (Anderberg [1]). The second phase assigns the vehicles to the respective routes. The third phase consists in solving each cluster by applying a Traveling Salesman Problem (TSP) heuristic that attributes, iteratively, a penalty to the arcs in which the vehicle capacity is exceeded in order to generate a feasible solution.

Halse [17] proposed a two phase heuristic for solving the VRPSPD which firstly consists of assigning the clients to the vehicles followed by an application of a 3-*opt* improvement heuristic.

Dethloff [9] developed an Cheapest Insertion based method in which the clients are added to the routes according to the following criteria: (1) distance; (ii) residual capacity; (iii) clients' distance to the depot.

Vural [35] developed two Genetic Algorithm (GA) approaches. The first one codifies the individuals using the Random Keys method while the second one was implemented as an improvement heuristic based on the GA structure developed by Topcuoglu e Sevilmis [33].

Gökçe [15] employed an Ant Colony approach that uses a 2-*opt* local search procedure in the pos-optimization phase.

Nagy and Salhi [23] developed an approach which combines different strategies used to solve the classical VRP such as: 2-*opt*, 3-*opt*, shift, swap, reverse and procedures to “repair” infeasible solutions.

Dell'Amico *et al*. [8] utilized a branch-and-price technique by employing two approaches: dynamic programming and state space relaxation.

Crispim and Brandão [6] proposed a hybrid approach combining the Tabu Search (TS) and Variable Neighborhood Descent (VND) metaheuristics. The sweep method was used to

generate an initial solution while shift and swap movements were utilized in the local search phase.

Röpke and Pisinger [26] developed a heuristic inspired on the Large Neighborhood Search (LNS) approach. The LNS is a local search based in two ideas for defining and exploring the neighborhood structures of large complexity. The first idea is to fix one part of the solution and hence define the solution space. The second one performs a search by applying constraint programming, integer programming and others.

Montané and Galvão [22] utilized the TS metaheuristic considering four neighborhood structures: shift, swap, cross and 2-*opt*. Both the first improvement and the best improvement approaches were adopted.

Chen [4] dealt with the VRPSPD by combining the Simulated Annealing (SA) and TS metaheuristics while Chen and Wu [5] developed a methodology based on the record-to-record travel approach, which in turn is a variation of the SA.

Constructive and improvement heuristics, as well as an algorithm based on the TS metaheuristic were presented by Bianchessi e Righini [3]. These approaches employed the node-exchange-based and arc-exchange-based movements.

Wassan *et al*. [36] proposed a reactive version of the TS metaheuristic. The sweep method was used to generate a initial solution while shift, swap and reverse movements were utilized in the local search phase.

Subramanian *et al*. [32] developed an algorithm based on the Iterated Local Search (ILS) approach, which uses the VND procedure in the local search. A constructive heuristic inspired on the algorithm proposed by Dethloff [9] was used to generate an initial solution. The VND explores the solution space by employing shifts, swap and cross movements. In case of improvement of the current solution an intensification is performed in the modified routes by means of the Or-*opt*, 2-*opt*, exchange and reverse movements. The perturbation mechanisms applied were ejection chain, double-wwap and double-bridge. The ejection chain consists in transfering a client from one route to an adjacent one. The double-swap consists in two consecutive swap movements. The double-bridge consists in removing four arcs and inserting another four in such away that a new route is generated. A detailed description of this algorithm, as well as a new mathematical formulation for the VRPSPD can be found in Subramanian [31].

Zachariadis *et al*. [37] proposed a hybrid heuristic for the VRPSPD which combines the TS and Guided Local Search metaheuristics.

In order to compare the literature approach, Dethloff [9] proposed a set of 40 instances with 50 clients. Salhy and Nagy [27] presented 28 instances with 50 to 199 clients, but half of them consider the time limit constraint. Finally, Montané and Galvão [22] proposed 18 instances involving 100, 200 and 400 clients.

To the best of our knowledge, the best results found in the literature for these instances belong to:

- Chen and Wu [5]: one instance of Salhi and Nagy [27];
- Röpke and Pisinger [26]: 26 instances of Dethloff [9];
- Wassan *et al*. [36]: 6 instances of Salhi and Nagy [27];
- Zachariadis *et al*. [37]: 6 instances of Salhi and Nagy [27] and 27 instances of Dethloff [9];
- Subramanian *et al*. [32]: all instances of Dethloff [9] and Montané and Galvão [22] and 17 of Salhi and Nagy [27].

This work presents a new heuristic algorithm to solve the VRPSPD. The proposed algorithm, called GENILS, combines the ILS, VND and an adaptation of the GENIUS heuristic. It differs from the one developed by Subramanian *et al*. [32] because the GENILS includes the GENIUS heuristic and the 3-*opt* and 4-*opt* procedures. The results obtained show that these strategies appeared to be efficient in the resolution of the problem.

The remainder of the paper is organized as follows. Section 2 describes the VRPSPD. Section 3 deals with the algorithm GENILS. Section 4 contains the results obtained by the proposed algorithm. Section 5 presents the concluding remarks and future works.

2. PROBLEM DESCRIPTION

The VRPSPD is a variant of the classical VRP. In this problem there is a depot with a homogeneous fleet with capacity Q and a set of N clients geographically dispersed. Each client $i \in N$ is associated with quantities d_i and p_i which represent, respectively, the delivery and pickup demands. The objective is to design a set of routes in such a way that sum of the travel costs are minimized and the following constraints are satisfied: (a) each route must start and end at the depot; (b) all clients must visited exactly once and by only one vehicle; (c) the delivery and pickup demands must be fully attended; (d) the vehicle load cannot be exceeded.

In some variants of this problem, one should include travel duration limits (distance or time) to accomplish a route. Fig. 1 illustrates an example of the VRPSPD.

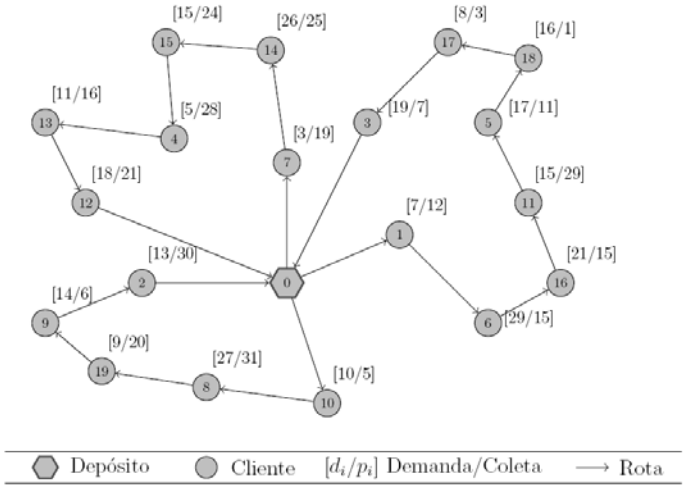

Figure 1: VRPSPD example

In Fig. 1, the clients are represented by integer numbers within the interval [1., |*N*|] while the depot is represented by 0. Each pair [d_i / pi] denotes, respectively, the delivery and pickup demands of a client i. In addition, there are three routes to be executed by vehicles with capacity Q = 150. In one of them, the vehicle leaves the depot and visits the clients 10, 8, 19, 9 and 2, returning to the depot at the end. In the first visit, the vehicle delivers 10 units and collects another 5 units, while in the last visit the vehicle delivers 13 units and collects another 30.

3. METHODOLOGY

This section presents the methodology developed to solve the VRPSPD. Subsection 3.1 describes how a initial solution is generated. Subsection 3.2 illustrates the neighborhood structures utilized to explore the solution space. Subsection 3.3 shows how a solution is evaluated. Subsection 3.4 presents the GENILS algorithm.

3.1 Constructive Heuristic

Three insertion based heuristics are employed to generate an initial solution. The first one, called CI-1R, is an adaptation of the Cheapest Insertion and the solution is build route by route. The second one, called CI-NR, was proposed by Subramanian *et al*. (2008) and it is based on the insertion heuristic of Dethloff [9]. The last one, VRGENIUS, is an adaptation of

the GENIUS heuristic (Gendreau *et al.*, 1992) originally proposed for the TSP and it is divided into two steps: construction (VRGENI) and improvement (VRUS). The VRGENI is an generalized insertion based method whose main characteristic is that the evaluation of the possible insertions of a client *i* is not necessarily limited to a position between two consecutive clients. The VRUS consists, at each iteration, in removing one client from the solution and re-inserting it in another position with a view of improving the current solution. This procedure ends when there is no more possibility of improvements. It is important to mention that both removal and insertion of a client is performed by applying 2-*opt* and 3-*opt* moves. The efficiency of these procedures relies in the fact that the solution space to be explored is restricted to the number of neighbors of each client. This number is determined by a parameter *p*.

3.2 Neighborhood Structures

In order to explore the solution space of the problem, the following seven neighborhood operators are applied: (a) *Shift*(1,0): one client *i* is transferred from a route r_1 to a route r_2; (b) *Shift*(2,0): two consecutive clients *i* and *j* are transferred from a route r1 to a route r_2; (c) *Swap*(1,1): one client *i* from a route r_1 is permuted with a client j from a route r_2; (d) *Swap*(2,1): two consecutive clients *i* and *j* from a route r_1 are permuted with a client *k* from a route r_2; (e) *Swap*(2,2): two consecutive clients *i* and *j* from a route r_1 are permuted with another two consecutive clients *k* and *l* from a route r_2; (f) M2-*opt*: two non-adjacent arcs are removed and another two are inserted in such a way that a new route is formed; (g) *k*Or-*opt*: *k* consecutive clients are removed and re-inserted in another position of the route. This last movement is a generalization of the Or-*opt* movement proposed by Or (1976). It's important to emphasize that only feasible movements are considered.

3.3 Evaluation Function

A solution *s* is evaluated by the function f presented in eq. (1). which determines the total travelled cost.

$$f(s) = \sum_{(i,j)\in A} c_{ij} x_{ij} \tag{1}$$

where:

N: set of clients plus the depot;

A: set of arcs (i, j), $i, j \in N$;

c_{ij}: travelled cost between i and j, $\forall\, i, j \in N$;

x_{ij}: indicates if the arc $(i, j) \in A$ is used ($x_{ij} = 1$) in the solution or not ($x_{ij} = 0$).

3.4 GENILS Algorithm

A hybrid algorithm, called GENILS, is proposed to solve the VRPSPD. This algorithm uses the method to generation an initial solution described in Subsection 3.2 and combines the Iterated Local Search – ILS (Stützle and Hoos, 1999), Variable Neighborhood Descent – VND (Hansen and Mladenović, 2001) and an adaptation of the GENIUS heuristic (Gendreau *et al*., 1992). The pseudo-code of the GENILS is presented in Fig. 2.

```
Algorithm GENILS
    s^A ← generate a solution by applying the CI-IR
    s^B ← generate a solution by applying the CI-NR
    s^C ← generate a solution by applying the VRGENIUS
    s^A ←VND(s^A)
    s^B ←VND(s^B)
    s^C ←VND(s^C)
    s ← s' | f(s') = min{f(s^A), f(s^B), f(s^C)}
    iter ← 0
    while (iter < iter_max) do
        iter ← iter + 1
        s' ← perturb(s)
        s'' ← VND(s)
        if ( f(s'') < f(s) ) then
            s ← s''
            iter ← 0
        end-if
    end-while
    return s
```

Figure 2 – Pseudo-code of the proposed algorithm

The GENILS algorithm starts generating three initial solutions, s^A, s^B, e s^C, each one of them by applying the methods described in Subsection 3.1. These solutions are improved by the VND and the best solution is used as initial solution s. In order to scape from the local optimum s, the solution is perturbed and a new solution s' is generated. Next, this perturbed solution is improved by the VND local search and a local optimum s'' is obtained. This perturbed solution becomes the new current solution in case s'' is better then s; otherwise, it is discarded and a new perturbation is performed from the solution s. This procedure is repeated until the maximum number of iterations without improvement of the current solution ($iter_{max}$) is archived.

The perturbations are performed by one of the three following mechanisms chosen at random.

- *Multiple Shifts*: Consists in performing *k Shift* movements (described in Subsection 3.2) successively. The value of *k* is randomly defined between 1, 2 or 3;
- *Multiple Swaps*: It follows the same idea of the previous perturbation, but *Swap* movements are applied.
- *Ejection Chain*: This movement was proposed by Rego and Roucairol (1996). First, a subset composed by *m* routes $R = \{r_1, r_2, ..., r_m\}$ is arbitrarily chosen. Next, a client is transferred from the route r_1 to the route r_2, then another client is transferred from a route r_2 to the route r_3 and so on until a client is transferred from the route r_m to the route r_1. In this perturbation, the clients are randomly selected.

The VND with random neighborhood ordering explores the solution space by means of the movements described in Subsection 3.2. An intensification phase is also embedded into to the VND procedure and it is performed using intra-route movements based on the following neighborhoods: *Shift*(1,0), *Shift*(2,0), *Swap*(1,1), 2-*Opt*, *Swap*(2,1), *Swap*(2,2) and *kOr-opt* with $k = 3, 4, 5$. In addition, this intensification phase also includes another two local search procedures, called *G3-opt* e *G4-op*t, which are based on the GENIUS heuristic. These movements are adaptations of the 3-*op*t and 4-*opt* neighborhoods. The adaptation consists in evaluating an arc insertion $(v_i; v_j)$ only if the clients v_i and v_j are relatively close. In view of this, define $N_p(v)$ as the set of *p* neighborhoods closest to the client *v* in a given route *r* of the solution *s*, where *p* is a parameter. Consider also the following definitions: N^r, set of all clients in route *r*; v_i: client $v_i \in N^r$; v_{h+1} and v_{h-1}: clients in route *r* which, respectively, succeeds and precedes the client $v_h \in N^r$; v_j: client $v_j \in N_p(v_i)$; v_k: client $v_k \in N_p(v_{i+1})$ in the path between v_j to v_i; v_l: client $v_l \in N_p(v_{j+1})$ in the path between v_i to v_j. The *G3-opt* works as follows: at each iteration, the arcs $(v_i; v_{i+1})$, $(v_j; v_{j+1})$ and $(v_k; v_{k+1})$ are removed and the arcs $(v_i; v_j)$, $(v_{i+1}; v_k)$ and $(v_{j+1}; v_{k+1})$ are inserted in the route *r*, in such a way that the solution *s* is improved and its cost is the least possible. It should be pointed out that both directions of the route *r* are examined. This procedure is repeated until is no longer possible to improve the solution *s*. The *G4-opt* procedure is similar to the *G3-opt* with the difference that, at each iteration, the arcs $(v_i; v_{i+1})$, $(v_{l-1}; v_l)$, $(v_j ; v_{j+1})$ and $(v_{k-1}; v_k)$ are removed and the arcs $(v_i; v_j)$, $(v_l; v_{j+1})$, $(v_{k-1}; v_{l-1})$ e $(v_{i+1}; v_k)$ are inserted. Finally, the *reverse* movement, which consists of inverting the route if there is

reduction in the maximum load of the vehicle, is applied. The pseudo-code of VND is presented in Fig. 3.

```
Procedure VND
  Let r the number of distinct neighborhoods
  RN ← set of neighborhoods described in section 3.2, in a random ordering
  i ← 1
  while (i ≤ r) do
    Let s_0 the best neighbor in RN^(k)(s) neighborhood
    if (f(s_0) < f(s)) then
      s ← s_0
      i ← 1
      { Intensification on the modified routes of s}
      s ← Local Search with Shift(1,0)
      s ← Local Search with Shift(2,0)
      s ← Local Search with Swap(1,1)
      s ← Local Search with M2-opt
      s ← Local Search with Swap(2,1)
      s ← Local Search with Swap(2,2)
      s ← Local Search with G3-opt
      s ← Local Search with G4-opt
      s ← Local Search with kOr-opt, k = 3, 4, 5
      s ← Reverse
    else
      i ← i + 1
    end-if
  end-while
  return s;
```

Figure 3 – Pseudo-code of VND

4. COMPUTATIONAL RESULTS

This section presents the computational results obtained by the GENILS, the hybrid heuristic algorithm proposed to solve the VRPSPD. The algorithm was coded in C++ using the Microsoft Visual C++, version 2005 and it was implemented in a Intel Core 2 Duo with 1.66 GHz and 2 GB of RAM memory running Windows Vista Home Premium 32 bits.

In order to validate the algorithm, the three set of test-problems presented in Section 1 were utilized, namely those of: Salhi and Nagy [27], Dethloff [9] and Montané and Galvão [22]. In the test-problems of Salhi and Nagy [27], only those without the time limit constraints were considered. The maximum number of iterations of the GENILS adopted was 10,000.

Tables 1, 2 and 3 compare the peformance of the GENILS with the different algorithms proposed in the literature. In these tables, the column *Problem* indicates the test-problem considered, *Best* is the best value found by the respective author(s) and *Time* is the execution time, in seconds, of the respective algorithm. The *Gap* column shows the percentual deviation

of the average solutions of the GENILS with respect to the best known solutions. The *Gap* is calculated by the expression *Gap* = 100 × (Average – Best) / Best (*Gap* column).

Table 1: Results obtained by the GENILS in the test-problems of Dethloff [9]

Problem	Röpke e Pisinger		Zachariadis *et al.*		Subramanian *et al.*		GENILS		
	Best	*Time*[(1)] (s)	Best	Time[(2)] (s)	Best	Time[(3)] (s)	Best	Time[(4)] (s)	*Gap* (%)
SCA3-0	636.10	232.00	636.06	2.83	**635.62**	0.90	**635.62**	6.77	0.00
SCA3-1	**697.80**	170.00	**697.84**	2.12	**697.84**	1.12	**697.84**	8.49	0.00
SCA3-2	**659.30**	160.00	**659.34**	2.58	**659.34**	1.19	**659.34**	8.13	0.00
SCA3-3	680.60	182.00	**680.04**	3.13	**680.04**	1.13	**680.04**	8.45	0.00
SCA3-4	**690.50**	160.00	**690.50**	2.68	**690.50**	1.32	**690.50**	8.09	0.00
SCA3-5	**659.90**	178.00	**659.90**	2.56	**659.90**	1.17	**659.90**	8.19	0.00
SCA3-6	651.10	171.00	**651.09**	4.40	**651.09**	1.23	**651.09**	8.21	0.00
SCA3-7	666.10	162.00	**659.17**	2.98	**659.17**	1.69	**659.17**	6.76	0.00
SCA3-8	**719.50**	157.00	**719.47**	3.98	**719.47**	1.08	**719.48**	8.85	0.00
SCA3-9	**681.00**	167.00	**681.00**	3.86	**681.00**	1.03	**681.00**	8.63	0.00
SCA8-0	975.10	98.00	**961.50**	3.21	**961.50**	2.52	**961.50**	5.65	0.00
SCA8-1	1052.40	95.00	1050.20	3.55	**1049.65**	2.98	**1049.65**	5.67	0.00
SCA8-2	1039.60	83.00	**1039.64**	4.67	**1039.64**	3.42	**1039.64**	5.92	0.00
SCA8-3	991.10	94.00	**983.34**	3.29	**983.34**	3.44	**983.34**	4.58	0.00
SCA8-4	**1065.50**	84.00	**1065.49**	2.68	**1065.49**	2.74	**1065.49**	5.98	0.00
SCA8-5	**1027.10**	96.00	**1027.08**	4.50	**1027.08**	3.44	**1027.08**	6.62	0.00
SCA8-6	972.50	93.00	**971.82**	2.67	**971.82**	2.48	**971.82**	6.57	0.00
SCA8-7	1061.00	92.00	1052.17	4.32	**1051.28**	5.39	**1051.28**	5.56	0.00
SCA8-8	**1071.20**	85.00	**1071.18**	3.43	**1071.18**	2.05	**1071.18**	5.57	0.00
SCA8-9	**1060.50**	86.00	**1060.50**	4.12	**1060.50**	3.10	**1060.50**	5.62	0.00
CON3-0	**616.50**	171.00	**616.52**	3.89	**616.52**	2.02	**616.52**	6.77	0.00
CON3-1	**554.50**	190.00	**554.47**	2.97	**554.47**	1.83	**554.47**	7.76	0.00
CON3-2	521.40	176.00	519.26	3.32	**518.00**	2.10	**518.01**	9.28	0.00
CON3-3	**591.20**	177.00	**591.19**	2.78	**591.19**	1.34	**591.19**	9.18	0.00
CON3-4	**588.80**	173.00	589.32	3.12	**588.79**	1.79	**588.79**	6.29	0.00
CON3-5	**563.70**	179.00	**563.70**	3.45	**563.70**	1.71	**563.70**	9.16	0.00
CON3-6	**499.10**	195.00	500.80	2.98	**499.05**	1.93	**499.05**	7.33	0.00
CON3-7	**576.50**	226.00	**576.48**	2.40	**576.48**	1.52	**576.48**	6.96	0.00
CON3-8	**523.10**	174.00	**523.05**	5.02	**523.05**	1.51	**523.05**	8.75	0.00
CON3-9	**578.20**	163.00	580.05	3.14	**578.24**	1.58	**578.25**	6.87	0.00
CON8-0	**857.20**	86.00	**857.17**	3.40	**857.17**	3.74	**857.17**	6.36	0.00
CON8-1	**740.90**	81.00	**740.85**	3.73	**740.85**	2.82	**740.85**	4.88	0.00
CON8-2	716.00	84.00	713.14	2.87	**712.89**	2.46	**712.89**	6.95	0.00
CON8-3	**811.10**	91.00	**811.07**	3.82	**811.07**	2.82	**811.07**	5.87	0.00
CON8-4	**772.30**	87.00	**772.25**	2.98	**772.25**	3.37	**772.25**	5.01	0.00
CON8-5	755.70	94.00	756.91	5.76	**754.88**	3.30	**754.88**	5.82	0.00
CON8-6	693.10	96.00	**678.92**	4.00	**678.92**	3.04	**678.92**	5.67	0.00
CON8-7	814.80	94.00	**811.96**	2.46	**811.96**	2.73	**811.96**	4.71	0.00
CON8-8	774.00	94.00	**767.53**	4.21	**767.53**	3.42	**767.53**	5.23	0.00
CON8-9	809.30	92.00	**809.00**	3.87	**809.00**	3.60	**809.00**	5.86	0.00

(1) CPU time in a Pentium IV 1.5 GHz.
(2) CPU time in a Pentium IV 2.4 GHz.
(3) CPU time in a Intel Core 2 Quad 2.5 GHz.
(4) CPU time in a Intel Core 2 Duo 1.6 GHz.

Table 2: Results obtained by the GENILS in the test-problems of Salhi and Nagy [27]

Problem	Wassan *et al.*		Zachariadis *et al.*		Subramanian *et al.*		GENILS		
	Best	*Time*(1) (s)	Best	Time(2) (s)	Best	Time(3) (s)	Best	Time(4) (s)	*Gap* (%)
CMT1X	468.30	48	469.80	2.89	**466.77**	1.10	**466.77**	7.82	0.00
CMT1Y	**458.96**	69	469.80	3.85	466.77	1.08	466.77	7.61	1.68
CMT2X	**668.77**	94	684.21	7.42	684.21	6.99	684.21	17.62	2.31
CMT2Y	**663.25**	102	684.21	8.02	684.21	5.84	684.21	20.10	3.16
CMX3X	729.63	294	**721.27**	11.62	721.40	6.80	721.40	59.61	0.02
CMT3Y	745.46	285	**721.27**	13.53	721.40	7.37	**721.27**	58.72	0.00
CMT12X	**644.70**	242	662.22	11.80	662.22	8.02	662.22	22.89	2.72
CMT12Y	**659.52**	254	662.22	7.59	662.22	7.32	663.50	22.33	0.60
CMT11X	861.97	504	**838.66**	17.78	839.39	12.58	846.23	48.85	0.90
CMT11Y	**830.39**	325	837.08	14.26	841.88	14.80	836.04	287.30	0.68
CMT4X	876.50	558	**852.46**	27.75	**852.46**	50.72	**852.46**	134.26	0.00
CMT4Y	870.44	405	852.46[a]	31.20	852.46	46.06	862.28	266.76	1.17[b]
CMT5X	1044.51	483	**1030.55**	51.67	**1030.55**	53.51	1033.51	768.94	0.29
CMT5Y	1054.46	533	**1030.55**	58.81	1031.17	58.74	1036.14	398.75	0.54

(1) CPU time in a Sun-Fire-V440 com um processador UltraSPARC-IIIi 1062 MHz.;
(2) CPU time in a Pentium IV 2.4 GHz.
(3) CPU time in a Intel Core 2 Quad 2.5 GHz.
(4) CPU time in a Intel Core 2 Duo 1.6 GHz.
(a) A best result of value 852.35 was found by Chen and Wu (2006).

Table 2: Results obtained by the GENILS in the test-problems of Montané and Galvão [22]

Problem	Montané and Galvão		Zachariadis *et al.*		Subramanian *et al.*		GENILS		
	Best	*Time*(1) (s)	Best	Time(2) (s)	Best	Time(3) (s)	Best	Time(4) (s)	*Gap* (%)
r101	1042.62	12.20	1019.48	10.50	1010.90	10.51	**1009.95**	35.65	-0.09
r201	671.03	12.02	666.20	8.70	**666.20**	6.24	**666.20**	39.62	0.00
c101	1259.79	12.07	1220.99	10.20	1220.26	12.73	**1220.18**	18.34	-0.01
c201	666.01	12.40	662.07	5.70	**662.07**	4.18	**662.07**	16.62	0.00
rc101	1094.15	12.30	1059.32	12.90	**1059.32**	9.48	**1059.32**	12.79	0.00
rc201	674.46	12.07	672.92	10.50	**672.92**	4.21	**672.92**	24.03	0.00
r1_2_1	3447.20	55.56	3393.31	61.80	3371.29	95.79	**3357.64**	175.81	-0.40
r2_2_1	1690.67	50.95	1673.65	47.40	**1665.58**	24.13	**1665.58**	103.44	0.00
c1_2_1	3792.62	52.21	3652.76	66.30	3640.20	95.17	**3636.74**	117.62	-0.10
c2_2_1	1767.58	65.79	1753.68	60.90	1728.14	41.94	**1726.59**	127.81	-0.09
rc1_2_1	3427.19	58.39	3341.25	45.30	3327.98	76.30	**3312.92**	299.30	-0.45
rc2_2_1	1645.94	52.93	1562.34	62.40	**1560.00**	34.28	**1560.00**	77.48	0.00
r1_4_1	10027.81	330.42	9758.77	315.30	9695.77	546.39	**9627.43**	2928.31	-0.71
r2_4_1	3685.26	324.44	3606.72	273.60	**3574.86**	231.73	3582.08	768.60	0.20
c1_4_1	11676.27	287.12	11207.37	283.50	11124.30	524.35	**11098.21**	1510.44	-0.23
c2_4_1	3732.00	330.20	3630.72	336.00	**3575.63**	293.18	3596.37	569.01	0.58
rc1_4_1	9883.31	286.66	9697.65	145.80	9602.53	550.90	**9535.46**	2244.18	-0.70
rc2_4_1	3603.53	328.16	3498.30	345.00	**3416.61**	291.15	3422.11	3306.84	0.16

(1) CPU time in an Athlon XP 2.0 GHz.
(2) CPU time in a Pentium IV 2.4 GHz.
(3) CPU time in a Intel Core 2 Quad 2.5 GHz.
(4) CPU time in a Intel Core 2 Duo 1.6 GHz.

In the test-problems developed by Dethloff [9], the GENILS obtained all the best known solutions. In the 14 test-problems of Salhi and Nagy [27], the proposed algorithm found 4 of

the best known solutions, with a maximum gap of 3,16% in the remaining problems. It is important to remark that none of the algorithms has a clear superiority in the terms of solution quality in these set of instances. The best performance of the GENILS was in the test-problems of Montané and Galvão [22], in which the proposed algorithm improved 9 of the best known solutions and equaled another 6, while in the 3 remaining test-problems the value of the maximum gap was 0.58%.

Comparing the GENILS with the other algorithms, it can be verified that proposed algorithm had a performance quite similar to the one developed by Subramanian *et al.* (2008). Indeed, in the test-problems of Dethloff [9] and Montané and Galvão (1999), both the algorithms taken together produced all the best results. In this second group of test-problems, the GENILS was superior in 9 problems and inferior in 3. On the other hand, in Salhi and Nagy [27] test-problems, the GENILS was superior in 2 cases and inferior in another 5.

A comparision in terms of execution time was not performed because the results found by the other algorithms were obtained using different machines.

5. CONCLUSIONS AND FUTURE WORKS

This work dealt with the Vehicle Routing Problem with Simultaneous Pickup and Delivery (VRPSPD). In order to solve it, a hybrid heuristic algorithm, called GENILS, was proposed. Adaptations of the Cheapest Insertion and the GENIUS heuristic were employed to generate an initial solution. To improve this solution, an Iterated Local Search (ILS) based procedure, that uses the Variable Neighborhood Descent (VND) method in the local search, was developed. The VND explores the solution space of the a solution by applying the following movements: *Shift*(1,0), *Shift*(2,0), *Swap*, *Swap*(2,1), *Swap*(2,2), *M2-Opt* and *kOr-Opt*. In case of improvement an intensification is performed in the modified routes using the following procedures: *G3-opt*, *G4-opt* (both based on the GENIUS heuristic) and *Reverse*.

From the results obtained, it can be observed that the proposed algorithm is competitive with the best approaches presented in the literature. Indeed, in a set of well-known test-problems, the GENILS was found capable to produce all the best results reported in the literature; in another one, 9 new solutions were generated and another 3 were equaled; and in a third set of instances, 3 best known solutions were equaled and the value of the maximum gap in the remaining problems of this set was of 3.16%. In addition, the GENILS obtained solutions with a variability smaller than 1% in 67 of the 72 test-problems, which corresponds

to 93% of the cases. One interesting behavior of the algorithm is the fact of obtaining a better performance in most test-problems of Montané and Galvão [22], illustrating its potential in solving real-life applications, where it is common to deal with large-scale problems.

As for future work, one can improve the *G3-opt* e *G4-opt* procedures by considering the recombination of multiple routes. In addition, it is strategic to combine the GENILS algorithm with the Tabu Search metaheuristic, where the latter can be triggered by replacing the VND, e.g. after a certain number of ILS iterations. This has to do with the fact that the Tabu Search is the base algorithm of those developed by Wassan *et al.* (2007) and Zachariadis *et al.*(2009), where both have obtained most of the best known results in the test-problems of Salhi and Nagy [27], and it was in this set that the GENILS had its worst performance.

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