Appendix A. Results for the OVRP

As it was mentioned, the published works on the OVRP are focused on heuristic methods. The results are mostly given for one of the two testbeds available in the literature. The first set contains small instances while the second set is reported contains larger instances. Table 1 contains a list of all OVRP instances used in this section and provides additional information on their origins and sizes. Let n be the number of customers, Q be the maximum carrying load and H be the maximum route length for the OVRP. As is the OVRP literature, the route limit is taken as the original value for the classical VRP multiplied by 0.9 which gives the value H. Let $K_{min} = \left\lceil \frac{\sum_{i \in \mathcal{V}} d_i}{Q} \right\rceil$ be a lower bound for the number of vehicles required.

Table 1. Configurations of the small and large OVRP test instances

Instance	**Origin**	n	Q	H	K_{min}
C1	Christofides et al. (1979)	50	160	∞	5
C2	Christofides et al. (1979)	75	140	∞	10
C3	Christofides et al. (1979)	100	200	∞	8
C4	Christofides et al. (1979)	150	200	∞	12
C5	Christofides et al. (1979)	199	200	∞	16
C6	Christofides et al. (1979)	50	160	180	5
C7	Christofides et al. (1979)	75	140	144	10
C8	Christofides et al. (1979)	100	200	207	8
C9	Christofides et al. (1979)	150	200	180	12
C10	Christofides et al. (1979)	199	200	180	16
C11	Christofides et al. (1979)	120	200	∞	7
C12	Christofides et al. (1979)	100	200	∞	10
C13	Christofides et al. (1979)	120	200	648	7
C14	Christofides et al. (1979)	100	200	936	10
F11	Fisher (1994)	71	30000	∞	4
F12	Fisher (1994)	134	2210	∞	7
O1	Li et al. (2007)	200	900	∞	5
O2	Li et al. (2007)	240	550	∞	9
O3	Li et al. (2007)	280	900	∞	7
O4	Li et al. (2007)	320	700	∞	10
O5	Li et al. (2007)	360	900	∞	8
O6	Li et al. (2007)	400	900	∞	9
O7	Li et al. (2007)	440	900	∞	10
O8	Li et al. (2007)	480	1000	∞	10

Small instances for the OVRP

There are 16 instances available in the literature. The 14 instances denoted C1–C14 are from Christofides et al. (1979) and the two instances denoted F11–F12 are from Fisher (1994). The test instances range in size from 50 to 199 customers and deal with a single depot and a single type of vehicle. Each instance includes capacity constraints while the instances C6–C10, C13 and C14 also have maximum route length restriction H and non-zero service times.

The performance of the proposed metaheuristic is compared with the best previously published OVRP algorithms which also considered the single objective (minimizing the cost of the generated routes). These are the two-phase heuristic (Sariklis and Powell 2000), BoneRoute (Tarantilis et al. 2004a), BATA (Tarantilis et al. 2004b), LBTA (Tarantilis et al. 2005), Broad Local Search Algorithm (BLSA) (Zachariadis and Kiranoudis 2010), BBMOOVRP (Marinakis and Marinaki 2014), the Honey Bees Mating Optimization algorithm (HBMOOVRP) (Marinakis and Marinaki 2011) and finally a Variable Neighborhood Search (Şevkli and Güler 2017). Table 2 summarizes the performance of the algorithm. For each method and each instance, we provide the best solution value ($Cost_{Best}$), the best running time in seconds if provided ($Time_{Best}$) and the gap (Gap %). Indeed, only three papers reported their average results for few instances without providing the average running time. In all tables, if an instance was not solved by a given method, we mention NS (not solved) and if a value is not reported we mention NF (not found).

Table 2 shows that most of the single-objective methods did not solve instances C6–C10, C13 and C14 of Christofides et al. (1979) because they did not consider the maximum route duration imposed on the OVRP in these instances. Also, only Zachariadis and Kiranoudis (2010) and (Şevkli and Güler 2017) solved Fisher (1994) instances.

The results of Table 2 show that no previous method reported solutions for all 16 instances, and most of them did not report solutions for all instances of a single set. Our proposed algorithm, on the other hand, provided high quality solutions for all 16 instances with an average gap less than 1% with respect to the best known solutions. Moreover, it improved the BKS for instance C14 by 0.68%. Finally, it is noteworthy that the running times are consistently low and average a bit more than 1 minute. Overall, we found solutions in which the total distance is equal, better or very close to the BKS.

It is worth mentioning that in the OVRP literature, no detailed information is provided by the authors on whether they report the time needed for finding the best solution or the total time required to run to completion. For example, Zachariadis and Kiranoudis (2010) set the computational time limit to 600 seconds for small OVRP instances and 1800 seconds for the large ones but provide, along with Marinakis and Marinaki (2011) and Tarantilis et al. (2004a), the elapsed time when the best solution was firstly encountered through the search process. Marinakis and Marinaki (2011) and Marinakis and Marinaki (2014) did not report the running time for most of the instances that they solved under the single-objective. The authors stated that the time needed is significantly low and it exceeds three minutes only for instances with 200 customers and more. However, the running time reported in all our tables corresponds to the total time elapsed. In addition, the difference of the compiler and hardware may affect the computational speed (as shown in Table 3). Consequently, regarding our running times, despite being quite satisfactory, a fair comparison in terms of computational efficiency is rather difficult and probably not useful, as it was mentioned by Zachariadis and Kiranoudis (2010) and Tarantilis et al. (2005).

Large instances for the OVRP

We now consider the large-scale instances developed by Golden et al. (1998) and adapted by Li et al. (2007) for the OVRP. There are eight instances with 200 to 480 customers without route-length restrictions as shown in Table 1. Each problem has a geometric symmetry with customers located in concentric circles around the depot. The presentation and heads in the tables are the same. To the best of our knowledge, Zachariadis and Kiranoudis (2010) and Şevkli and Güler (2017) are the only published works that solved the single objective large-scale OVRP instances. Table 4 compares our best results against textbfthe BKS.

On the large-scale instances, our method is as efficient as it was on the Christofides et al. (1979) instances. The gap ranges from 0.19% to 2.47% with an average of **1.18%**. Due to their characteristics (large number of customers, large vehicle capacity, symmetry), the large-scale instances may require much more diversification. As mentioned above, in terms of computational times, an analytic comparison is not possible as the running time depends on a variety of factors.

Altogether, the performance of the metaheuristic is very satisfactory, given that many of its features were designed to act on multi-depots. We are then able to compete with the current state-of-the-art methods. Indeed, the main focus of this paper is to propose an efficient solution method for the MDOVRP, consequently, the code used to solve MDOVRP is the same one used to solve OVRP instances. The slightly high gaps on some instances represents the cost to pay when the method implemented is able to solve a wider range of multi-constrained problems.

To assess the robustness of the proposed method, we report in Table 5 the average and the

Table 2. Comparison with the state-of-the art methods on small OVRP test instances

Instance	**BKS**	**2-phase heuristic**			**BoneRoute**			**BATA**			**LBTA**			**VNS**		
	Cost	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)
C1	412.96	488.20	0.22	18.22	412.96	7.20	0.00	412.96	38.62	0.00	412.96	1725.00	0.00	416.06	0.46	0.75
C2	564.06	795.30	0.16	41.00	564.06	25.80	0.00	564.06	68.89	0.00	564.06	3672.60	0.00	567.14	46.44	0.55
C3	639.26	815.00	0.94	27.49	641.77	28.80	0.39	642.42	56.54	0.49	639.57	3226.80	0.05	639.74	12.09	0.08
C4	733.13	1034.14	0.88	41.06	735.47	75.00	0.32	736.89	81.69	0.51	733.68	5047.80	0.08	733.13	63.71	0.00
C5	869.00	1349.71	2.20	55.32	877.13	225.60	0.94	879.73	98.13	1.23	870.26	5788.20	0.14	871.27	596.95	0.26
C6	412.96	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C7	568.49	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C8	644.63	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C9	756.38	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C10	875.67	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C11	678.54	828.25	1.54	22.06	679.38	29.40	0.12	679.6	37.67	0.16	678.54	1521.60	0.00	682.81	53.08	0.63
C12	534.24	882.26	0.76	65.14	534.24	14.40	0.00	534.24	84.54	0.00	534.24	3875.40	0.00	534.24	2.94	0.00
C13	896.50	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C14	591.87	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
F11	177.00	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	177.00	74.58	0.00
F12	761.68	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	770.17	749.38	1.11

Instance	**BLSA**			**HBMOOVRP**			**BBMOOVRP**			**HALNS**			**Other Config.**
	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)	*NewBest*
C1	412.96	24.00	0.00	412.96	10.20	0.00	412.96	9	0.00	412.96	6.00	0.00	-
C2	564.06	55.00	0.00	564.06	25.20	0.00	564.06	23.4	0.00	564.06	13.00	0.00	-
C3	639.26	106.00	0.00	640.08	33.00	0.13	639.26	31.2	0.00	643.33	35.00	0.64	-
C4	733.13	167.00	0.00	738.49	NF	0.73	735.18	NF	0.28	738.06	94.00	0.67	-
C5	869.00	256.00	0.00	878.25	183.00	1.06	872.15	180.6	0.36	873.13	196.00	0.48	-
C6	NS	NS	NS	412.96	NF	0.00	412.96	NF	0.00	413.74	7.00	0.19	-
C7	NS	NS	NS	575.25	22.20	1.19	568.95	21	0.08	571.47	15.00	0.52	-
C8	NS	NS	NS	644.63	NF	0.00	644.63	NF	0.00	645.16	40.00	0.08	-
C9	NS	NS	NS	761.41	69.00	0.67	757.24	67.2	0.11	764.72	119.00	1.10	-
C10	NS	NS	NS	884.28	NF	0.98	879.38	NF	0.42	888.01	259.00	1.41	-
C11	678.54	87.00	0.00	680.15	70.20	0.24	678.54	69	0.00	722.08	74.00	6.42	-
C12	534.24	29.00	0.00	536.37	NF	0.40	535.28	NF	0.19	546.10	35.00	2.22	-
C13	NS	NS	NS	898.18	81.00	0.19	897.10	76.8	0.07	911.40	100.00	1.66	-
C14	NS	NS	NS	593.95	NF	0.35	592.16	NF	0.05	**587.82**	42.00	-0.68	**586.64**
F11	177.00	83.00	0.00	NS	NS	NS	NS	NS	NS	177.39	15.00	0.22	-
F12	761.68	189.00	0.00	NS	NS	NS	NS	NS	NS	765.90	86.00	0.56	-
Avg												0.97	

- 2-phase heuristic (Sariklis and Powell 2000)
- BoneRoute (Tarantilis et al. 2004a)
- BATA (Tarantilis et al. 2004b)
- LBTA (Tarantilis et al. 2005)
- VNS (Şevkli and Güler 2017)
- BLSA (Zachariadis and Kiranoudis 2010)
- HBMOOVRP (Marinakis and Marinaki 2011)
- BBMOOVRP (Marinakis and Marinaki 2014)

Table 3. Configuration of computers used to run the OVRP state-of-the-art methods

Method	**Computer characteristics**
This paper	Intel Core i7-4770 3.4 GHz
Two-phase heuristic Sariklis and Powell (2000)	Pentium 133-16 MB RAM
BoneRoute Tarantilis et al. (2004a)	Pentium II 400MHz -128 MB RAM
BATA Tarantilis et al. (2004b)	Pentium II 400MHz-128 MB RAM
LBTA Tarantilis et al. (2005)	Pentium II 400MHz -128 MB RAM
BLSA Zachariadis and Kiranoudis (2010)	T5500 1.66 GHz
HBMOOVRP Marinakis and Marinaki (2011)	Intel Core 2 DUO CPU T9550 2.66 GHz
BBMOOVRP Marinakis and Marinaki (2014)	Intel Core 2 DUO CPU T9550 2.66 GHz
VNS Şevkli and Güler (2017)	Core i5 2.8 GHz

best results and running time on large and small OVRP instances. The results in Table 5 show the robustness and the stability of our algorithm as it consistently achieves results with very low variability over 10 runs on the same instance. The average deviation between the average and the best results obtained over the 10 runs on all OVRP instances is of only 1.03%

Table 4. Comparison with the state-of-the art methods on large OVRP test instances

Instance	**BKS**	**BLSA**			**VNS**			**HALNS**		
	Cost	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)	$Cost_{Best}$	$Time_{Best}$	*Gap* (%)
O1	5988.35	5988.35	648.00	0.00	6018.52	7.90	0.50	6000.00	246.00	0.19
O2	4549.46	4549.46	804.00	0.00	4568.85	2232.70	0.43	4661.72	386.00	2.47
O3	7731.00	7731.00	864.00	0.00	7731.00	174.49	0.00	7794.48	596.00	0.82
O4	7251.30	7251.30	1058.00	0.00	7260.89	7199.60	0.13	7330.69	959.00	1.09
O5	9152.47	9152.47	956.00	0.00	9200.18	3450.76	0.52	9271.17	1370.00	1.30
O6	9790.00	9793.47	1180.00	0.04	9790.00	5779.06	0.00	9901.44	2058.00	1.14
O7	10347.70	10347.70	1332.00	0.00	10357.40	10204.95	0.09	10464.86	2652.00	1.13
O8	12392.00	12412.26	1582.00	0.16	12392.00	14262.20	0.00	12550.21	3404.00	1.28
Avg			1053.00	0.02		5413.95	0.21		1458.87	1.18

Table 5. Average vs best HALNS results on small and large OVRP instances

Instance	$Cost_{Avg}$	$Time_{Avg}$	$Cost_{Best}$	$Time_{Best}$
C1	414.08	6.00	412.96	6.00
C2	570.45	12.90	564.06	13.00
C3	648.34	32.40	643.33	35.00
C4	744.52	98.50	738.06	94.00
C5	887.48	208.00	873.13	196.00
C6	416.34	6.70	413.74	7.00
C7	577.29	15.50	571.47	15.00
C8	650.70	40.40	645.16	40.00
C9	770.82	130.60	764.72	119.00
C10	898.08	265.10	888.01	259.00
C11	738.22	61.90	722.08	74.00
C12	558.69	38.50	546.10	35.00
C13	934.19	103.00	911.40	100.00
C14	595.66	47.00	587.82	42.00
F11	180.25	16.50	177.39	15.00
F12	782.96	81.50	765.90	86.00
Avg	-	72.78	-	71.00
O1	6000.00	247.80	6000.00	246.00
O2	4692.43	398.90	4661.71	386.00
O3	7821.19	634.60	7794.48	596.00
O4	7371.82	1046.40	7330.69	959.00
O5	9318.18	1398.60	9271.17	1370.00
O6	9943.10	2096.90	9901.44	2058.00
O7	10514.29	2802.90	10464.86	2652.00
O8	12588.96	3534.00	12550.21	3404.00
Avg	-	1520.01	-	1458.87