Supplementary Material of "A Collaborative Drone-Truck Delivery System with Memetic Computing Optimization"

Ruonan Zhai, *Student Member, IEEE,* Yi Mei, *Senior Member, IEEE,* Tong Guo, *Student Member, IEEE,* and Wenbo Du, *Member, IEEE*

S.I. Detailed Results on the Small Dataset

Table SI shows the summarized results of CPLEX and MATSP-D on the small dataset [1]. Each group contains 10 instances with N uniformly distributed customers. We conducted the Wilcoxon rank sum test to compare the results of MATSP-D with the optimum. The optimal result is marked with $(+)$, if MATSP-D performs significantly worse than the optimum, and $(=)$ if there is no statistical difference. For each group, the summary results are listed in the "W-D" row. "W" indicates the number of $(+)$, and "D" the number of $(=)$.

From the table, we can see that MATSP-D consistently reached the optimum on 22 out of the 30 instances. The average gap from the optimum over all the instances is as small as 0.1%.

An interesting observation is that the standard deviation of MATSP-D is always zero, even when the solution is not optimal. In other words, MATSP-D converges to the same sub-optimal solution in all the runs. We further looked into the solutions of the MATSP-D for these instances and compared with the optimal solutions, and found that the optimal solutions require the drone to depart and return to the same truck node. The representation of MATSP-D (each operation must have different start and end nodes) does not allow such a situation. However, MATSP-D still obtains the optimal solutions with the assumption that the drone must depart and return to different truck nodes.

TABLE SI
THE MEAN (STD) OF MATSP-D AND RUNTIME OVER 30 INDEPENDENT RUNS ON THE SMALL INSTANCES.

Instance	CPLEX	Time(s)	MATSP-D	Std	Time(s)
U-n10-51	250.7(=)	45	250.7	0.0	4
U-n10-52	189.5(+)	48	191.3	0.0	5
U-n10-53	192.2(=)	43	192.2	0.0	4
U-n10-54	224.9(=)	41	224.9	0.0	5
U-n10-55	253.1(=)	39	253.1	0.0	5
U-n10-56	226.9(=)	37	226.9	0.0	5
U-n10-57	197.2(+)	59	197.5	0.0	4
U-n10-58	213.3(=)	38	213.3	0.0	7
U-n10-59	204(=)	52	204	0.0	5
U-n10-60	225.9(+)	44	226	0.0	4
W-D	3-7	-	-	-	-
Avg.	217.8	45	218.0	0.0	5
Instance	**CPLEX**	**Time(s)**	**MATSP-D**	**Std**	**Time(s)**
U-1-n11	221.2(+)	433	223.4	0.0	10
U-2-n11	205.8(=)	542	205.8	0.0	5
U-3-n11	193(=)	655	193	0.0	5
U-4-n11	241.3(=)	395	241.3	0.0	5
U-5-n11	248.1(=)	386	248.1	0.0	5
U-6-n11	217.7(=)	523	217.7	0.0	6
U-7-n11	237.3(=)	727	237.3	0.0	5
U-8-n11	214.8(=)	418	214.8	0.0	5
U-9-n11	256.3(+)	682	256.8	0.0	5
U-10-n11	227.9(=)	635	227.9	0.0	5
W-D	2-8	-	-	-	-
Avg.	226.3	540	226.6	0.0	5
Instance	**CPLEX**	**Time(s)**	**MATSP-D**	**Std**	**Time(s)**
U-1-n12	239.7(=)	5264	239.7	0.0	6
U-2-n12	221.3(=)	5824	221.3	0.0	8
U-3-n12	247.1(+)	6255	247.5	0.0	7
U-4-n12	230(=)	8469	230	0.0	7
U-5-n12	243.3(=)	7645	243.3	0.0	7
U-6-n12	222(=)	5249	222	0.0	6
U-7-n12	225.8(=)	5702	225.8	0.0	7
U-8-n12	227.9(+)	6759	229.3	0.0	8
U-9-n12	243.9(=)	5313	243.9	0.0	6
U-10-n12	196.1(+)	6698	198.8	0.0	7
W-D	3-7	-	-	-	-
Avg.	229.7	6318	230.2	0.0	7

S.II. Detailed Results on The First Large DataSet

Table SII-SX shows the detailed results of the four compared algorithms on the nine groups of the first large instances. Each group is distinct in three distributions (uniform, single-center and double-center), and three ratios between truck and drone speeds ($\alpha = c^d/c = 1, 2, 3$). Each row shows the cost and runtime of the compared deterministic algorithms. As MATSP-D was run 30 times independently for each instance, we first calculate the mean and standard deviation over the 30 runs for each instance, and then present the average of the mean cost and standard deviation over the 10 instances in the table. We conducted Wilcoxon rank sum test between MATSP-D and the compared algorithms. The compared result is marked with $(+)$, if it performs significantly better than MATSP-D, $(=)$ if there is no statistical difference, and $(-)$ if it performs significantly worse than MATSP-D. For each scale, the summary results are listed in the "W-D-L" row. "W" indicates the number of $(+)$, "D" the number of $(=)$, and "L" the number of $(-)$.

TABLE SII
THE AVERAGE PERFORMANCE AND RUNTIME OF THE COMPARED ALGORITHMS ON THE UNIFORM DATASET WITH $\alpha = 1$

Instance		TSP-EP [1]		TSP-GP [1]		TSP-MC [2]		HGVNS [3]		MATSP-D		
N	id	Cost	Time(s)	Cost	Time(s)	Cost	Time(s)	Avg.Cost	Time(s)	Avg.Cost	Std	Time(s)
50	71	479.8(+)	13	530.1(-)	1	529.9(-)	2	506.2(-)	2	481.2	1.8	86
	72	510.6(+)	18	600(-)	1	568.5(-)	1	541.7(-)	2	513.6	5.2	137
	73	488.3(+)	15	563.8(-)	1	568.6(-)	1	518.6(-)	1	491.3	2.7	148
	74	484.5(-)	10	560.2(-)	1	541(-)	1	526.5(-)	2	483.9	1.6	142
	75	523.4(-)	8	578.9(-)	1	571.7(-)	1	555.2(-)	1	516.1	5	146
	76	470.5(+)	14	534.6(-)	1	552.4(-)	1	505.3(-)	2	472.4	3.6	156
	77	513.7(=)	14	583.6(-)	1	602.1(-)	1	545.7(-)	1	513.1	4.4	138
	78	506.8(-)	21	554(-)	1	569.4(-)	1	550.5(-)	1	492.9	2.8	166
	79	466.7(-)	15	522.2(-)	1	533.7(-)	2	533.7(-)	2	464.5	3.5	131
	80	458(-)	7	501.1(-)	1	503.2(-)	2	501.4(-)	2	452.7	3.3	73
W-D-L		4-1-5	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
75	81	575.5(=)	176	644.1(-)	6	670.7(-)	6	621.6(-)	7	575.9	5.6	334
	82	527.8(+)	262	600.9(-)	3	612.9(-)	5	558.6(-)	6	530	2.6	340
	83	544.8(=)	201	609(-)	5	602(-)	7	588.3(-)	8	544.9	4.9	358
	84	566.9(+)	324	651.1(-)	4	646.6(-)	6	636.8(-)	7	574.4	5.5	353
	85	599.5(=)	234	689.5(-)	2	696.8(-)	5	671(-)	6	598.4	7.1	347
	86	579(=)	216	695.2(-)	1	645.3(-)	6	645.3(-)	6	579.8	4.3	342
	87	579.2(+)	198	674.4(-)	2	646.8(-)	7	631(-)	9	587	5.1	366
	88	601.3(-)	234	655.9(-)	5	678.9(-)	6	634.7(-)	8	580.9	5.7	360
	89	526.7(-)	185	591.6(-)	5	599.7(-)	7	560.4(-)	9	518.8	7.3	348
	90	565.9(-)	160	653.3(-)	4	660.6(-)	6	651.8(-)	7	563.2	4.4	369
W-D-L		3-4-3	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
100	91	676(+)	595	749.3(-)	11	769.7(-)	18	726.3(-)	23	678.7	5.9	1109
	92	615.8(=)	774	683.8(-)	12	700.9(-)	21	676.4(-)	23	615.8	6.5	1080
	93	610.2(+)	898	701.6(-)	11	707.7(-)	22	678.7(-)	25	613.2	5.1	1025
	94	634.2(+)	1239	734.3(-)	9	719.5(-)	24	673.8(-)	27	639.7	6.5	1056
	95	651.3(+)	394	728.3(-)	10	763.1(-)	23	700.5(-)	27	657.6	6.2	1091
	96	649.9(=)	863	725.3(-)	15	758(-)	23	730.1(-)	27	654.1	9.1	1087
	97	674.1(=)	1263	763.9(-)	8	766.1(-)	22	730(-)	25	673.9	6.8	1131
	98	620.7(+)	557	738(-)	12	720.7(-)	26	671.3(-)	29	628.3	7.2	1047
	99	652.3(=)	1217	731.1(-)	13	742.3(-)	27	723.2(-)	29	653.8	7.9	1113
	100	669.7(-)	653	746.9(-)	16	749.8(-)	26	749.8(-)	27	651.7	13	1041
W-D-L		5-4-1	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-

It is shown that MATSP-D significantly outperforms TSP-GP, TSP-MC and HGVNS for all 270 instances. Compared with TSP-EP, the performance is comparable when $\alpha = 1$ (32 wins and 32 losses). When $\alpha = 2$, MATSP-D significantly outperforms TSP-EP on 60 instances, while losing on only 16 instances. When $\alpha = 3$, MATSP-D shows significantly better performance than TSP-EP on 81 out of the 90 instances.

S.III. CONVERGENCE CURVES

Fig. S1 shows the convergence curves of the compared algorithms on three representative instances: (a) U_3-75-n50 (b) U_3-100-n100 and (c) berlin52 with $\alpha = 1$. From Fig. 1(a), we can see that when $N = 50$, MATSP-D converged slightly more slowly than TSP-GP, but similar to other compared algorithms. It can reach better solutions than all the other algorithms. Note that TSP-GP, TSP-MC and HGVNS had much shorter convergence curves than TSP-EP and MATSP-D, since they are designed as fast heuristics and have much shorter computational complexity than TSP-EP and MATSP-D. They are deterministic algorithms, and thus we cannot extend their runtime to further improve their performance. In fact, the original literature [1] already showed that TSP-EP can achieve better final performance than TSP-GP, although with higher computational complexity. From Fig. 1(b), we see similar patterns. MATSP-D had slightly slower convergence than TSP-GP, TSP-MC and HGVNS, but the same as TSP-EP at the beginning. After around 100 seconds, TSP-EP started to stagnate and its curve became flatter. However, MATSP-D can still improve substantially, and reached much better final solutions than TSP-EP.

In Fig. 1(c), the final performance and runtime of HGVNS and HGA were directly obtained from their literature, which are plotted as two points in the figure. Since the compared algorithms were implemented on different computers, normalization has been carried out to make fair comparisons on runtime. That is, all the runtimes presented in this experiment were obtained by dividing the runtimes in the original publications by some factors. To be specific, HGA was implemented on Intel Core i7-6700 (3.4GHz); therefore the runtimes presented in [4] were divided by 2.4/3.4. We can observe consistent patterns with that on the other two instances. Furthermore, we can directly obtain the results of HGA on this instance from [4]. Since HGA is the only population-based algorithm among the five compared algorithms, comparison between MATSP-D and HGA might be of particular interest. The figure shows that if given the

TABLE SIII
THE AVERAGE PERFORMANCE AND RUNTIME OF THE COMPARED ALGORITHMS ON THE UNIFORM DATASET WITH $\alpha = 2$

Instance		TSP-EP [1]		TSP-GP [1]		TSP-MC [2]		HGVNS [3]		MATSP-D		
N	id	Cost	Time(s)	Cost	Time(s)	Cost	Time(s)	Avg.Cost	Time(s)	Avg.Cost	Std	Time(s)
50	71	404.9(-)	25	422.1(-)	1	508.2(-)	2	455.8(-)	3	388.3	2.6	137
	72	429.1(-)	60	459.3(-)	1	558(-)	2	497.3(-)	2	422.9	2.4	90
	73	399.2(-)	20	418.4(-)	2	550.8(-)	2	446.6(-)	2	398	3.2	91
	74	417.7(-)	25	424.6(-)	1	500.5(-)	2	425.3(-)	2	411.9	1.6	95
	75	445.4(-)	25	464.7(-)	1	555.4(-)	2	480.8(-)	2	415.9	3.5	88
	76	370.7(+)	33	397.7(-)	2	509.2(-)	2	444.8(-)	3	374.4	2.1	89
	77	433.6(-)	22	446(-)	1	584.3(-)	1	465.4(-)	2	416.7	4.3	94
	78	436.9(-)	32	448.4(-)	1	562.9(-)	2	459(-)	2	422.2	1.6	90
	79	381.7(+)	75	409.6(-)	1	524(-)	2	524(-)	2	384.4	3.6	85
	80	379.5(-)	23	391.6(-)	1	471.7(-)	3	391.3(-)	3	368.3	2.9	102
W-D-L		2-0-8	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
75	81	481.7(-)	427	504(-)	8	649.8(-)	9	557(-)	10	471.5	6.7	493
	82	454.1(-)	239	475.8(-)	4	601.5(-)	8	502(-)	10	440.2	4.3	483
	83	455.1(-)	393	466.4(-)	4	570.2(-)	11	504.7(-)	13	446.5	6.7	448
	84	470.8(=)	533	500(-)	5	622.6(-)	9	622.6(-)	9	472.8	5.4	422
	85	508.9(-)	229	534(-)	6	678.1(-)	7	572.1(-)	9	486.2	6.5	555
	86	488.9(-)	415	512(-)	6	616.6(-)	9	604.4(-)	10	469.1	7	461
	87	473.2(=)	523	491.9(-)	6	628.1(-)	11	573.5(-)	13	471.7	5.4	451
	88	508.9(-)	340	529.4(-)	6	651.5(-)	8	567(-)	10	462.7	4	436
	89	446.9(-)	535	458.5(-)	5	576.1(-)	9	467.7(-)	11	428.6	7.2	431
	90	462.9(=)	335	482.5(-)	8	643.4(-)	8	523.7(-)	10	463.6	7.5	466
W-D-L		0-3-7	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
100	91	565.7(-)	3186	585.1(-)	18	761(-)	24	634.2(-)	30	559.7	7.5	1546
	92	517.7(-)	2914	533.2(-)	19	679.6(-)	28	594.6(-)	30	499.2	7.6	1394
	93	526.2(-)	2393	546.4(-)	15	683.3(-)	25	563.4(-)	32	501.7	8	1458
	94	541.8(-)	2295	558.2(-)	21	711.3(-)	26	609.9(-)	29	534.2	9.4	1435
	95	549.3(-)	1451	560.9(-)	20	758.3(-)	24	595.7(-)	27	538.7	6.4	1575
	96	555(-)	1729	577.2(-)	18	739.1(-)	26	636.9(-)	32	545	8.2	1469
	97	582.8(-)	2505	607.1(-)	21	742(-)	26	662(-)	34	563.2	8.9	1508
	98	520.1(=)	1085	529.4(-)	20	681.1(-)	29	583.7(-)	35	522.2	5.6	1567
	99	556(-)	1438	577.4(-)	16	719.5(-)	34	643.8(-)	41	544.3	5.4	1537
	100	571(-)	1728	596.6(-)	20	730.1(-)	29	656.8(-)	32	535.7	8.3	1498
W-D-L		0-1-9	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-

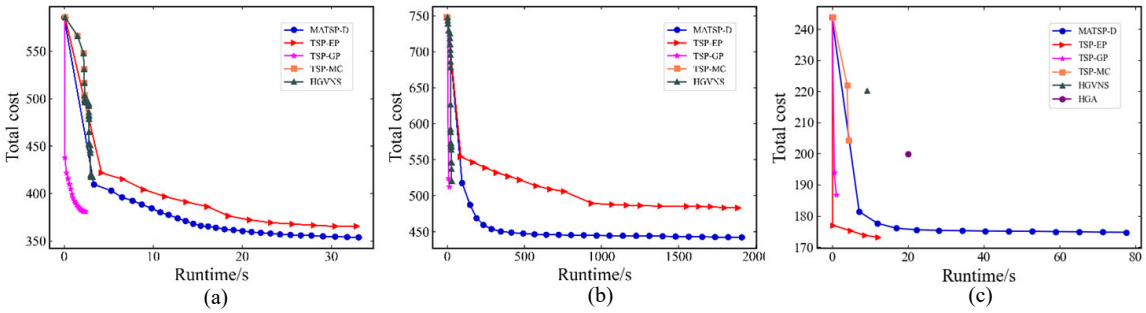

Fig. S1. The convergence curves of the compared algorithms on (a) U_3-75-n50 (b) U_3-100-n100 and (c) berlin52 ($\alpha = 1$).

same runtime as in [4], MATSP-D can converge to much better solutions than HGA.

REFERENCES

[1] N. Agatz, P. Bouman, and M. Schmidt, "Optimization approaches for the traveling salesman problem with drone," *Transp. Sci.*, vol. 52, no. 4, pp. 965–981, 2018.

[2] C. C. Murray and A. G. Chu, "The flying sidekick traveling salesman problem: Optimization of drone-assisted parcel delivery," *Transp. Res. Pt. C-Emerg. Technol.*, vol. 54, pp. 86–109, 2015.

[3] J. C. de Freitas and P. H. V. Penna, "A variable neighborhood search for flying sidekick traveling salesman problem," *Int. Trans. Oper. Res.*, vol. 27, no. 1, pp. 267–290, 2020.

[4] Q. M. Ha, Y. Deville, Q. D. Pham, and M. H. Hà, "A hybrid genetic algorithm for the traveling salesman problem with drone," *J. Heuristics*, vol. 26, no. 2, pp. 219–247, 2020.

TABLE SIV
THE AVERAGE PERFORMANCE AND RUNTIME OF THE COMPARED ALGORITHMS ON THE UNIFORM DATASET WITH $\alpha = 3$

Instance		TSP-EP [1]		TSP-GP [1]		TSP-MC [2]		HGVNS [3]		MATSP-D		
N	id	Cost	Time(s)	Cost	Time(s)	Cost	Time(s)	Avg.Cost	Time(s)	Avg.Cost	Std	Time(s)
50	71	365.4(-)	33	380.8(-)	3	496.1(-)	2	452.9(-)	3	349.9	3.5	161
	72	392.4(-)	48	427.7(-)	1	551.5(-)	2	453(-)	2	384.4	2.8	114
	73	383(-)	31	394.8(-)	2	536.3(-)	2	394.3(-)	2	364.6	2.5	125
	74	390.1(-)	27	396.1(-)	2	490.2(-)	2	439(-)	2	372.7	3.7	119
	75	415.1(-)	32	414.4(-)	3	538.3(-)	2	482.5(-)	2	364.3	2.6	115
	76	347.9(-)	30	363.6(-)	2	481.4(-)	2	427.5(-)	3	333.7	3	119
	77	386.6(-)	38	396.3(-)	2	572.9(-)	2	440.6(-)	2	377.6	2.7	109
	78	397.4(-)	30	424.9(-)	2	560.5(-)	1	451.5(-)	2	369.7	3.8	105
	79	365.1(-)	40	366.7(-)	2	518.5(-)	2	433.1(-)	2	334.2	2.9	131
	80	359.4(-)	45	371.7(-)	1	460.2(-)	2	378.5(-)	3	336.1	3	108
W-D-L		0-0-10	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
75	81	457.3(-)	710	468.5(-)	9	637.9(-)	8	515.4(-)	9	425.3	7.2	597
	82	433.6(-)	376	434.8(-)	9	594(-)	7	456.8(-)	9	403.9	4.9	542
	83	407.8(-)	367	426.9(-)	8	576.5(-)	10	470(-)	12	393.7	5	668
	84	438.1(-)	434	441(-)	11	616.7(-)	8	488.8(-)	10	414.1	5.9	629
	85	467.4(-)	472	474.9(-)	12	670.5(-)	7	546.1(-)	8	445.6	4.9	705
	86	450.4(-)	539	452.9(-)	10	605(-)	9	590.3(-)	11	408.7	6.1	625
	87	438.5(-)	548	454.3(-)	11	595.8(-)	11	518.3(-)	11	415.1	4.2	573
	88	485.5(-)	486	504(-)	10	639.9(-)	8	537(-)	9	410.5	4.6	608
	89	420.1(-)	344	429(-)	10	569.3(-)	9	477.1(-)	11	390.5	6.1	625
	90	426.7(-)	530	431.8(-)	11	617.3(-)	8	616.9(-)	9	414	7.8	670
W-D-L		0-0-10	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
100	91	531.2(-)	2226	538.2(-)	31	759.4(-)	22	584.9(-)	26	501.2	6.6	2206
	92	482.4(-)	2488	511.7(-)	24	678.8(-)	26	550.8(-)	31	442.2	7.6	1909
	93	484.6(-)	2772	499.5(-)	33	676.4(-)	24	523.5(-)	30	446	7.2	1981
	94	506.4(-)	2477	528.2(-)	32	705.4(-)	25	594(-)	29	476.1	10.7	2014
	95	502.3(-)	2814	528.9(-)	26	757.2(-)	23	557(-)	32	484.8	5.8	2258
	96	523(-)	2918	528.5(-)	29	724.3(-)	25	585.7(-)	29	501.5	3.4	1944
	97	547.9(-)	2966	563(-)	33	739.9(-)	24	582.3(-)	34	493.4	15	1978
	98	479.6(-)	1828	499.2(-)	29	691.1(-)	26	547.7(-)	30	461.9	9.6	2200
	99	524.3(-)	2040	531.9(-)	31	707.9(-)	31	578.9(-)	40	498.5	7.4	1920
	100	539.3(-)	2122	547.8(-)	35	715.4(-)	28	676.8(-)	31	474.5	15.2	2245
W-D-L		0-0-10	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-

TABLE SV
THE AVERAGE PERFORMANCE AND RUNTIME OF THE COMPARED ALGORITHMS ON THE SINGLE-CENTER DATASET WITH $\alpha = 1$

Instance		TSP-EP [1]		TSP-GP [1]		TSP-MC [2]		HGVNS [3]		MATSP-D		
N	id	Cost	Time(s)	Cost	Time(s)	Cost	Time(s)	Avg.Cost	Time(s)	Avg.Cost	Std	Time(s)
50	71	564.1(-)	16	664.8(-)	1	613.4(-)	2	610(-)	2	550.6	2.4	85
	72	623.2(=)	12	731.9(-)	1	738.1(-)	2	685(-)	2	622.9	4.2	160
	73	470.5(-)	20	534.7(-)	2	581.3(-)	2	520.1(-)	2	468.9	4.5	164
	74	711.9(-)	26	842.2(-)	1	805.7(-)	2	791.9(-)	2	695.8	3.1	156
	75	722.7(-)	23	878.5(-)	1	814.7(-)	2	772.1(-)	2	705.9	8.1	178
	76	696.1(-)	8	837.8(-)	1	745.5(-)	2	745.5(-)	2	687.9	7.7	160
	77	567.8(=)	11	681.8(-)	1	603(-)	2	602.7(-)	2	569.3	4.2	193
	78	719.9(=)	5	789.3(-)	0	743.6(-)	2	743.6(-)	2	719.1	4.2	138
	79	587.3(-)	16	672.7(-)	1	648.2(-)	2	614.3(-)	2	577.1	5.7	91
	80	744.9(-)	7	900.4(-)	1	822.4(-)	2	803.7(-)	3	721.7	6	85
W-D-L		0-3-7	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
75	81	952.2(+)	369	1128.7(-)	5	1161.6(-)	7	1005(-)	7	959	13.9	394
	82	762.3(=)	149	922.8(-)	4	817.2(-)	11	811.3(-)	12	761.7	8.4	353
	83	788.9(+)	274	904.1(-)	4	897.2(-)	7	854(-)	8	796.9	6.3	365
	84	884.8(+)	113	989(-)	4	1014.8(-)	8	947.4(-)	9	893.8	10.1	367
	85	743.3(+)	175	956.2(-)	4	809.8(-)	8	795.3(-)	8	759.2	6.9	399
	86	941.9(=)	77	1100.7(-)	5	1121.6(-)	7	1040.3(-)	8	939.9	9.3	401
	87	903.2(-)	197	1025.2(-)	5	1030.9(-)	7	966.6(-)	9	897.9	9.4	394
	88	864.2(+)	179	1089.5(-)	4	927.7(-)	10	920.7(-)	11	881.4	11.9	416
	89	815.4(-)	89	915.8(-)	5	881.5(-)	9	859.9(-)	10	808.4	12.7	376
	90	937.2(-)	169	1099.9(-)	5	1138.3(-)	7	1076.5(-)	8	929.5	14.6	372
W-D-L		5-2-3	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
100	91	987.5(+)	521	1209.1(-)	12	1144(-)	26	1105.6(-)	29	996	15.1	1141
	92	1112.4(=)	865	1302.4(-)	10	1291.7(-)	23	1197.8(-)	25	1111.9	15.2	1114
	93	1097.2(=)	660	1282.7(-)	5	1186.9(-)	26	1162(-)	29	1096.6	12.4	1129
	94	1234.6(-)	740	1430.6(-)	8	1388(-)	23	1387.6(-)	24	1208.5	15.1	1136
	95	958.9(=)	906	1133.5(-)	13	1100.5(-)	27	1045.3(-)	28	964.6	12.7	1112
	96	1076.3(-)	992	1264.8(-)	13	1171.9(-)	30	1090.1(-)	32	1056.3	13.1	1119
	97	1069.4(+)	982	1295.3(-)	11	1188(-)	27	1159.6(-)	29	1086.7	8.9	1187
	98	1030.7(=)	1198	1208(-)	13	1165.1(-)	34	1108.2(-)	35	1034.5	13.2	1205
	99	846.8(=)	847	952.7(-)	17	1021.2(-)	22	947.5(-)	24	847.9	8.8	1123
	100	962.6(-)	750	1119.5(-)	14	1079.6(-)	25	1079.6(-)	27	954.8	10.8	1090
W-D-L		2-5-3	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-

TABLE SVI
THE AVERAGE PERFORMANCE AND RUNTIME OF THE COMPARED ALGORITHMS ON THE SINGLE-CENTER DATASET WITH $\alpha = 2$

Instance		TSP-EP [1]		TSP-GP [1]		TSP-MC [2]		HGVNS [3]		MATSP-D		
N	id	Cost	Time(s)	Cost	Time(s)	Cost	Time(s)	Avg.Cost	Time(s)	Avg.Cost	Std	Time(s)
50	71	457.7(-)	21	480.3(-)	2	602.3(-)	2	505.7(-)	2	437.3	6.4	98
	72	484.3(+)	17	533.8(-)	1	730.4(-)	2	566.2(-)	2	489.4	6.2	200
	73	375.1(-)	16	410(-)	1	564.8(-)	2	457.3(-)	2	368	3.4	178
	74	556.2(-)	31	597.2(-)	1	729.4(-)	2	693.5(-)	3	545.1	9.7	187
	75	587.1(-)	24	648.1(-)	1	798(-)	2	702.5(-)	2	572.9	7.5	181
	76	569.6(-)	22	634.2(-)	1	734.9(-)	2	664.3(-)	2	552.7	6.6	198
	77	439.9(-)	16	489.1(-)	2	572.4(-)	2	543.2(-)	2	436.6	4.9	186
	78	553.5(+)	53	628.6(-)	1	691(-)	2	671.7(-)	3	559.8	5.7	83
	79	463.4(-)	70	483.2(-)	2	639.3(-)	2	513.8(-)	2	450	6.8	93
	80	576.8(-)	24	643.1(-)	2	717.4(-)	2	672.9(-)	3	565.4	10.1	91
W-D-L		2-0-8	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
75	81	734.1(-)	504	803.4(-)	8	1017.4(-)	9	840(-)	11	724.3	15.6	447
	82	596.9(-)	298	650.4(-)	7	769.5(-)	11	736.9(-)	12	588.1	11.9	460
	83	640.7(-)	309	664.8(-)	9	879.5(-)	8	735.1(-)	9	626	7.8	522
	84	738.5(-)	260	785(-)	9	955.5(-)	9	811.6(-)	10	710.6	9.2	506
	85	589.5(+)	282	636.4(-)	7	739.5(-)	9	697.2(-)	10	601.1	8.6	453
	86	743.9(=)	291	804.2(-)	8	1104.5(-)	7	828.5(-)	8	746.9	16.3	476
	87	711.9(=)	453	781.4(-)	9	1024(-)	7	868.8(-)	8	709.5	12.7	485
	88	697.5(+)	232	770.2(-)	8	860.3(-)	15	847.7(-)	16	707.7	12.4	443
	89	665.8(-)	353	709.7(-)	6	841.6(-)	9	773.3(-)	11	657.1	8.4	505
	90	743(-)	414	807.3(-)	10	1088.2(-)	7	855.2(-)	10	722.3	10.9	508
W-D-L		2-2-6	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
100	91	820(-)	1250	869(-)	17	1099.2(-)	28	916.4(-)	32	801	14.7	1449
	92	877.3(+)	1481	944.1(-)	24	1243(-)	26	1059.2(-)	29	888.1	19.8	1477
	93	932.2(-)	1904	969.1(-)	22	1135.7(-)	27	1018.7(-)	30	883.1	17.1	1743
	94	987.4(-)	1679	1026.3(-)	23	1311.5(-)	25	1108.2(-)	29	976.1	16.4	1416
	95	735.7(+)	2276	792.6(-)	23	1072.5(-)	29	879.3(-)	33	760.3	14.1	1545
	96	813.1(+)	1984	912.6(-)	18	1093.4(-)	33	962(-)	37	842.6	19.8	1480
	97	843.7(+)	1829	943.5(-)	20	1129.8(-)	29	976.7(-)	33	853.9	16.2	1677
	98	824.7(-)	1483	916.7(-)	21	1026.1(-)	34	913.2(-)	38	806.2	12.3	1405
	99	699.3(-)	2055	737.2(-)	25	990.2(-)	25	775.9(-)	31	683.4	10.4	1643
	100	805.5(-)	2273	835.8(-)	20	1042.8(-)	25	916.1(-)	29	782.1	14.3	1668
W-D-L		4-0-6	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-

TABLE SVII
THE AVERAGE PERFORMANCE AND RUNTIME OF THE COMPARED ALGORITHMS ON THE SINGLE-CENTER DATASET WITH $\alpha = 3$

Instance		TSP-EP [1]		TSP-GP [1]		TSP-MC [2]		HGVNS [3]		MATSP-D		
N	id	Cost	Time(s)	Cost	Time(s)	Cost	Time(s)	Avg.Cost	Time(s)	Avg.Cost	Std	Time(s)
50	71	410.5(-)	74	436(-)	2	588.6(-)	2	470.1(-)	2	386.2	4.3	145
	72	433.8(=)	52	465.4(-)	2	724.2(-)	2	525.8(-)	2	433.7	4.9	109
	73	322(-)	41	339.9(-)	2	549.2(-)	2	361.7(-)	2	309	3.4	109
	74	484(-)	90	514(-)	2	715.7(-)	2	589.8(-)	3	467.2	7.8	120
	75	499.3(-)	41	539.5(-)	2	745.3(-)	2	610.9(-)	2	481.8	7.8	99
	76	531.2(-)	34	550.9(-)	1	720.7(-)	1	546.6(-)	2	486.8	7.6	107
	77	384.6(-)	25	401.1(-)	2	552.8(-)	2	436.7(-)	2	368.1	4.3	109
	78	467.6(-)	29	523.4(-)	2	646.8(-)	2	594.8(-)	2	453.3	6.5	98
	79	379.3(-)	41	427.6(-)	2	639.3(-)	2	432.4(-)	2	374.1	5.2	94
	80	479(-)	47	543.2(-)	2	681.8(-)	3	639.6(-)	3	473.8	9	101
W-D-L		0-1-9	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
75	81	650.9(-)	362	715(-)	8	964.1(-)	9	664.7(-)	11	621.7	13.4	540
	82	505.9(-)	633	550.7(-)	10	757(-)	10	584(-)	15	498.9	9.7	507
	83	564.3(-)	554	572.8(-)	11	855.8(-)	7	675.2(-)	9	556.5	9.6	576
	84	666.1(-)	489	676.1(-)	10	935(-)	9	769.4(-)	10	622.7	10.1	553
	85	535.8(-)	503	548.7(-)	10	723.5(-)	9	622.7(-)	10	522.4	9.9	505
	86	685.5(-)	731	724.7(-)	9	1075.1(-)	7	777.2(-)	8	657	13.3	535
	87	590.2(=)	707	648.7(-)	10	1009.4(-)	7	697.4(-)	8	592.6	10.2	544
	88	659(-)	470	685.8(-)	11	818.9(-)	16	818.9(-)	16	617.9	13.7	504
	89	562.5(=)	804	576.5(-)	13	843.5(-)	9	667.5(-)	11	563.6	10.2	547
	90	665.7(-)	612	712(-)	11	1075.2(-)	7	773.2(-)	9	640.3	7.8	544
W-D-L		0-2-8	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
100	91	712.5(-)	2100	752.9(-)	24	1081.8(-)	28	798(-)	35	698.6	13.2	1696
	92	789.6(-)	3497	806.5(-)	33	1206.2(-)	25	906.8(-)	34	756.6	15.5	1675
	93	875.3(-)	3488	881.1(-)	27	1112.5(-)	27	918.6(-)	33	779.3	16	1964
	94	837.1(-)	2901	916(-)	33	1253.1(-)	25	1051.4(-)	27	823.6	16.2	1586
	95	632.5(+)	3614	684.3(-)	25	1040.7(-)	28	791(-)	33	647.1	18.7	1740
	96	757.9(-)	2258	779.3(-)	25	1079.4(-)	31	1079.4(-)	33	722.9	16.1	1711
	97	741.7(+)	2176	781.1(-)	35	996.4(-)	31	901.8(-)	34	756.8	14.2	1870
	98	685(=)	2085	731.9(-)	35	948.9(-)	37	766.6(-)	42	685.1	18.3	1672
	99	611.8(-)	2142	643.3(-)	32	947(-)	24	764.1(-)	28	594.9	12.8	1735
	100	721(-)	1635	760.6(-)	26	1014.7(-)	27	864.3(-)	30	691.1	13.6	2084
W-D-L		2-1-7	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-

TABLE SVIII
THE AVERAGE PERFORMANCE AND RUNTIME OF THE COMPARED ALGORITHMS ON THE DOUBLE-CENTER DATASET WITH $\alpha = 1$

Instance		TSP-EP [1]		TSP-GP [1]		TSP-MC [2]		HGVNS [3]		MATSP-D		
N	id	Cost	Time(s)	Cost	Time(s)	Cost	Time(s)	Avg.Cost	Time(s)	Avg.Cost	Std	Time(s)
50	71	1060.7(=)	8	1260.3(-)	2	1178(-)	2	1110.7(-)	2	1057.4	8.1	120
	72	989.2(-)	8	1134.2(-)	1	1170.7(-)	2	1082(-)	2	985.6	8	86
	73	900.6(-)	10	1101.2(-)	1	1004(-)	2	1004(-)	2	893.5	7.7	82
	74	903.7(+)	13	1012.3(-)	1	1080.5(-)	1	950.1(-)	1	910.5	7.4	81
	75	1017.1(=)	10	1170.1(-)	1	1185(-)	2	1055.8(-)	2	1016.1	5	85
	76	1044.1(-)	8	1280.9(-)	2	1171.9(-)	2	1142(-)	3	1029.3	8	85
	77	961.2(+)	10	1098.4(-)	1	1048.4(-)	2	1048.4(-)	2	966.2	5.4	87
	78	949.6(+)	22	1173.1(-)	1	1167.3(-)	1	1020.7(-)	2	961.7	8.3	86
	79	955.7(=)	18	1091.3(-)	1	1080.4(-)	1	1080.2(-)	2	957.9	4.8	85
	80	1070.5(-)	22	1202(-)	1	1196.7(-)	2	1127.2(-)	2	1067.9	7.6	79
W-D-L		3-3-4	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
75	81	1091.6(+)	129	1247.8(-)	3	1292(-)	8	1188(-)	9	1107.4	8.5	406
	82	1170.2(-)	150	1380.8(-)	6	1363.1(-)	6	1303.8(-)	8	1161.3	13.2	424
	83	1128.7(-)	98	1312(-)	5	1231.6(-)	9	1179.9(-)	10	1121.8	8.1	421
	84	1452.3(-)	235	1680.7(-)	4	1646.5(-)	8	1630.1(-)	8	1416.1	18.6	368
	85	1356.3(=)	179	1742.8(-)	4	1575.4(-)	7	1490.6(-)	9	1357.8	12.7	413
	86	1130.4(+)	98	1359.3(-)	3	1262.5(-)	7	1218.8(-)	8	1139	4.7	367
	87	1196.9(=)	161	1392.1(-)	4	1446(-)	6	1307.7(-)	8	1198.1	10.6	367
	88	1353.9(+)	312	1697.6(-)	4	1553.3(-)	9	1521.1(-)	10	1372.7	9.7	433
	89	1159.7(+)	220	1399.4(-)	6	1335.6(-)	7	1234.4(-)	8	1167.2	12.6	391
	90	1100.8(=)	158	1262.7(-)	7	1205.3(-)	10	1184.6(-)	12	1101.9	7	405
W-D-L		4-3-3	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
100	91	1318.6(+)	667	1609.6(-)	12	1572.4(-)	22	1527.5(-)	25	1332.9	13.5	1099
	92	1312.2(-)	1156	1485.3(-)	17	1483.2(-)	22	1468.2(-)	24	1301.6	11.3	1234
	93	1216.5(+)	1440	1407.9(-)	18	1407.5(-)	23	1304.8(-)	25	1233.2	9.1	1203
	94	1332.5(=)	2064	1552.5(-)	20	1517.8(-)	28	1439.2(-)	29	1328.2	17.1	1158
	95	1395.5(+)	1359	1717.4(-)	16	1601.2(-)	24	1543.5(-)	26	1431.6	12.3	1178
	96	1486.5(-)	1191	1684(-)	12	1635.8(-)	25	1622.4(-)	30	1459.5	14.9	1174
	97	1487.7(+)	723	1779.6(-)	15	1690.3(-)	29	1638.4(-)	31	1506.5	16.7	1138
	98	1397.4(-)	863	1565.7(-)	17	1518.1(-)	27	1467.2(-)	29	1385.3	18.6	1220
	99	1250.6(+)	1095	1557.1(-)	15	1422.9(-)	27	1387.6(-)	30	1263.2	11.4	1176
	100	1407.1(+)	1444	1740.7(-)	18	1595.7(-)	30	1564.8(-)	32	1421.3	11.1	1230
W-D-L		6-1-3	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-

TABLE SIX
THE AVERAGE PERFORMANCE AND RUNTIME OF THE COMPARED ALGORITHMS ON THE DOUBLE-CENTER DATASET WITH $\alpha = 2$

Instance		TSP-EP [1]		TSP-GP [1]		TSP-MC [2]		HGVNS [3]		MATSP-D		
N	id	Cost	Time(s)	Cost	Time(s)	Cost	Time(s)	Avg.Cost	Time(s)	Avg.Cost	Std	Time(s)
50	71	871.8(-)	22	946.6(-)	2	1106.9(-)	2	960(-)	2	836.4	20.1	133
	72	823.1(-)	20	908.5(-)	2	1105.8(-)	2	1105.8(-)	2	806.8	9.3	82
	73	756.9(-)	18	769.7(-)	2	953.4(-)	2	879(-)	2	725.7	7.8	83
	74	705.3(+)	55	776.5(-)	2	1073.2(-)	1	788(-)	2	710.1	7.1	88
	75	847.2(-)	20	914.3(-)	1	1169.6(-)	1	959.7(-)	2	836.5	10.3	85
	76	856(-)	22	942.1(-)	1	1102.1(-)	2	902.5(-)	3	810.1	7.3	84
	77	736.6(=)	28	785.4(-)	2	1028(-)	2	961.1(-)	3	738.1	8.6	96
	78	762.5(-)	22	816.8(-)	1	1096.9(-)	2	1095.2(-)	2	747	6.9	88
	79	814.8(-)	20	851.4(-)	1	1076.3(-)	1	1076.3(-)	1	787	11.2	88
	80	871.9(=)	36	950(-)	2	1113.1(-)	2	991.8(-)	3	871.3	4.9	89
W-D-L		1-2-7	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
75	81	868.1(+)	452	969.5(-)	10	1279.9(-)	7	957.4(-)	10	873	10.2	434
	82	919.2(-)	420	1021.8(-)	6	1297.5(-)	7	1074.8(-)	9	906.9	11.5	420
	83	894.7(-)	470	992.9(-)	9	1100.2(-)	14	1077.1(-)	15	881.3	8.3	435
	84	1150.1(=)	575	1287.4(-)	12	1619.1(-)	8	1594.3(-)	9	1149	14.9	418
	85	1067.8(=)	458	1201.2(-)	8	1436.1(-)	7	1241.2(-)	10	1073.4	18	423
	86	928.8(+)	319	974.7(-)	8	1219(-)	8	1098.1(-)	12	932.5	9.3	448
	87	944.5(+)	252	1009.2(-)	9	1412.8(-)	7	1052.4(-)	11	953	10.3	394
	88	1171(-)	291	1241.4(-)	9	1477.2(-)	11	1271.4(-)	12	1096.9	21.4	444
	89	998.3(-)	358	1081.8(-)	9	1330(-)	7	1111.4(-)	10	940.6	13.8	437
	90	861.2(-)	492	973.3(-)	9	1019.4(-)	14	991.6(-)	15	853.7	8.7	409
W-D-L		3-2-5	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
100	91	1063.4(=)	1751	1142.2(-)	23	1515.9(-)	23	1326.9(-)	27	1058.6	13.1	1330
	92	1013.3(=)	1761	1140.7(-)	26	1460.9(-)	23	1169.6(-)	30	1014.3	15.1	1260
	93	1041(-)	1935	1087.5(-)	22	1374.5(-)	23	1161.6(-)	27	1014.5	12.7	1414
	94	1092.2(=)	2581	1205.6(-)	25	1470.1(-)	29	1295.5(-)	32	1095	19	1361
	95	1131(-)	2372	1230.3(-)	18	1557.9(-)	25	1357.8(-)	31	1115.3	13	1338
	96	1210.9(-)	2003	1280.7(-)	30	1551.5(-)	27	1406.3(-)	31	1188.9	16.5	1367
	97	1247.5(-)	1869	1392.3(-)	24	1550.2(-)	32	1344.6(-)	36	1240.6	12.8	1354
	98	1154.1(=)	3009	1195.7(-)	28	1461.8(-)	31	1292.2(-)	37	1148.7	15.7	1563
	99	1008.6(+)	1612	1098.1(-)	22	1333.7(-)	27	1206.3(-)	32	1020.7	10.1	1396
	100	1113.7(+)	1380	1248.4(-)	29	1494.1(-)	32	1325.6(-)	38	1144.3	11.7	1305
W-D-L		2-4-4	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-

TABLE SX
THE AVERAGE PERFORMANCE AND RUNTIME OF THE COMPARED ALGORITHMS ON THE DOUBLE-CENTER DATASET WITH $\alpha = 3$

Instance		TSP-EP [1]		TSP-GP [1]		TSP-MC [2]		HGVNS [3]		MATSP-D		
N	id	Cost	Time(s)	Cost	Time(s)	Cost	Time(s)	Avg.Cost	Time(s)	Avg.Cost	Std	Time(s)
50	71	787.8(-)	44	822(-)	3	1062.4(-)	2	878.2(-)	3	730.1	7.5	146
	72	750(-)	42	802.5(-)	2	1099.8(-)	1	1099.8(-)	2	691	8.5	100
	73	671.6(-)	59	725.4(-)	2	967.8(-)	2	909.9(-)	2	654.5	6.7	96
	74	658.2(-)	25	662.8(-)	2	1060.4(-)	1	720.5(-)	2	624.5	4.6	95
	75	795.7(-)	36	790.2(-)	4	1146.4(-)	1	875.6(-)	2	735.5	7.9	104
	76	797.1(-)	24	791.4(-)	3	1074.9(-)	2	942.7(-)	3	722.8	7	92
	77	700.4(-)	23	704.1(-)	2	995.3(-)	2	833.8(-)	3	656.7	6.9	97
	78	693.8(-)	35	694.6(-)	2	1096.9(-)	2	1095.2(-)	2	653	4.4	94
	79	737.5(-)	33	759.3(-)	2	1059.5(-)	2	1041.8(-)	2	691.4	7	95
	80	831.6(-)	47	854.8(-)	3	1056.7(-)	2	895.1(-)	3	794.1	9.9	104
W-D-L		0-0-10	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
75	81	784.2(-)	684	816(-)	12	1243.2(-)	8	878.1(-)	10	768.3	8.4	515
	82	816.9(-)	714	850.9(-)	14	1281.3(-)	7	1036.6(-)	9	802.3	10.9	594
	83	789.3(=)	617	835.1(-)	12	983.3(-)	15	899.2(-)	19	787.4	5.3	535
	84	1021.2(-)	974	1076.5(-)	15	1618.6(-)	8	1285.4(-)	11	980.3	12.2	483
	85	970.5(-)	502	1014.5(-)	9	1402.1(-)	8	1155.5(-)	11	932.6	15.5	487
	86	858.6(-)	523	926.8(-)	7	1196.7(-)	8	1196.7(-)	9	816.5	10.2	475
	87	843.2(-)	389	908.4(-)	11	1399.3(-)	6	965(-)	10	837.9	10.4	470
	88	957.4(-)	739	1077.3(-)	10	1374.1(-)	15	1116.8(-)	16	910.2	17.3	468
	89	869.7(-)	502	940.3(-)	10	1286.3(-)	8	945.5(-)	11	826.4	10.1	478
	90	802.7(-)	364	838.7(-)	10	951.7(-)	17	867.6(-)	22	763.9	8.9	520
W-D-L		0-1-9	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-
100	91	922(=)	2440	971.4(-)	38	1503.1(-)	23	1206.9(-)	30	922.8	14.9	1578
	92	896.5(-)	3223	985.6(-)	29	1359.7(-)	24	1008.5(-)	30	863.1	14.7	1404
	93	911.8(-)	4255	1005.6(-)	29	1376.6(-)	24	1079.6(-)	28	902.7	11.5	1582
	94	951.1(=)	4048	1017.2(-)	43	1366.2(-)	34	1151.2(-)	40	960.3	23.9	1529
	95	982.6(-)	2606	1048.5(-)	29	1511.2(-)	26	1178(-)	30	974.8	14.7	1658
	96	1104.9(-)	3356	1116.1(-)	39	1511.6(-)	29	1342.5(-)	34	1037.2	17.4	1570
	97	1167.2(-)	1444	1198.4(-)	39	1480.2(-)	35	1188(-)	43	1088.5	19	1539
	98	1086.8(-)	2009	1126.6(-)	29	1452.6(-)	32	1286.2(-)	35	1026.3	18	1732
	99	924.1(-)	1495	961.6(-)	27	1309.7(-)	27	1179.4(-)	30	906.5	10.6	1667
	100	1021.5(-)	1984	1070(-)	37	1422.5(-)	30	1249(-)	34	993.1	9.8	1531
W-D-L		0-2-8	-	0-0-10	-	0-0-10	-	0-0-10	-	-	-	-