Tailoring Evolutionary Algorithms to Solve the Multi-Objective Location-Routing Problem for Biomass Waste Collection – Supplementary Material

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This supplementary material includes:

- A. Discuss on the pitfalls of GA and ACO in solving the MOLRP
- B. Detailed Computational Results on LRP Datasets
- C. Comparison of Different Mutation Operators of MPGA
- D. An Example of the Confliction Between the Objectives
- E. Investigation on the Population Division Method of MPGA
- F. Investigation on the Pheromone Segregation Strategy of SPACO

A. *Discuss on the Pitfalls of GA and ACO in Solving the MOLRP*

We investigate the pitfalls of GA and ACO in solving the MOLRP as a complement to *Section II-C*.

For GAs, there are a wide range of generic solvers for multi-objective optimization problems. They mainly focus on the improvement of the selection operators as the crossovers and mutation operators should be designed to fit the specific problem [1], [2]. When applying generic operators on MOLRPs, problems may be encountered as shown in Fig. 1(a). As a part of the network, $parent_1$ provides the solution “1-4-5-6-1; 2-7-8-9-2” as demonstrated by the blue route, while $parent_2$ gives “2-4-7-8-2; 3-9-5-6-3” of the yellow route. Though these two solutions hold different location decisions, they can have good performances in the objective space, because tracking the non-dominant front allows for a diverse solution set. When mating these two parent solutions to produce offspring solutions, two types of offsprings can lead to deterioration: (i) $offspring_1$ inherits part of the routing information from both parent

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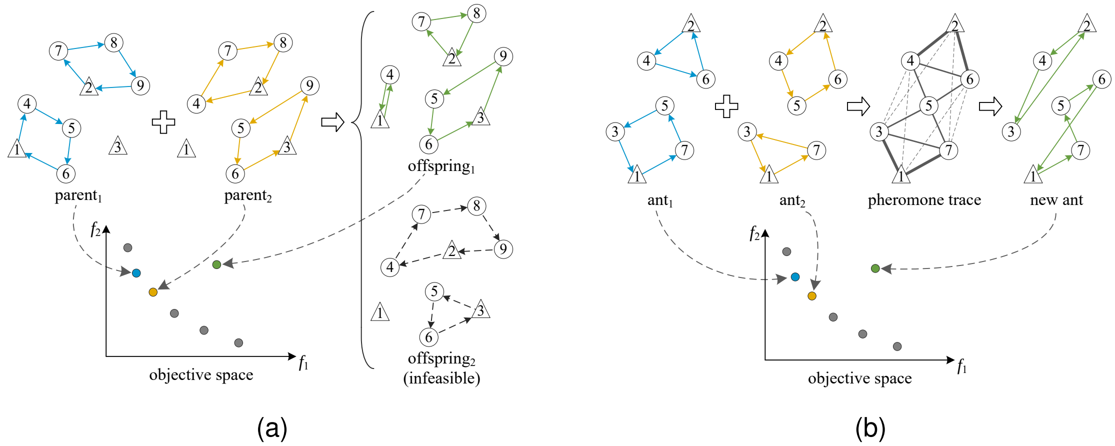

Fig. 1. Pitfalls for GA and ACO in solving MOLRP. (a) GA (b) ACO.

solutions, easily to create a union of the location solutions, which adds the facility cost and even increases the total routing distance; (ii) $offspring_2$ merges two feasible sub-routes into a large one, failing to satisfy the capacity constraint. These solutions can make the algorithm inefficient.

ACO is widely used in routing-based problems [3], [4]. It mimics the similar activity of ant colony tracing the path. Therefore, it is easy to construct feasible solutions by adding routing rules for ants. ACO tracks the best route by adjusting the pheromone on each arc. As it is designed for single-objective discrete optimization problems, ACO usually keeps one pheromone matrix and takes the same heuristic information for all ants. To apply ACO to multi-objective optimization problems, two main ways are developed namely multi-pheromone ACO (MPACO) [5] and multi-colony ACO (MCACO) [6]. MPACO sets specifically designed heuristic information and different pheromone matrices for every objective function, and multiplying them together when calculating the probability of selecting the next node into the route. MCACO takes different colonies. Each colony independently updates its route with respect to an objective function, and updates the pheromone according to the fitness of all colonies. Essentially, MPACO operates by converting the multi-objective optimization problem into a single-objective one, while MCACO offers different operators for every objective function [7]. Though these methods have been used widely in many multi-objective optimization applications [8]–[10], there are still drawbacks in solving the MOLRP. As Fig. 1(b) shows, ant_1 and ant_2 are two elite solutions that will leave a large quantity of pheromone on their respective route. Note that customer node 5 belongs to different satellite depots in these two solutions. This will cause the pheromone traces fused into a misleading one: A new ant starting from satellite depot 1 and reaching at customer 5 may be misled to 6 to generate a bad solution.

The pitfalls of GA and ACO have a common reason: Integrating the information of two solutions $(\mathbf{z}_1, \mathbf{y}_1, \mathbf{x}_1)$, $(\mathbf{z}_2, \mathbf{y}_2, \mathbf{x}_2)$ can lead to a worse one, because $(\mathbf{z}_1, \mathbf{y}_1) \neq (\mathbf{z}_2, \mathbf{y}_2)$. That is, the strategy of planning a good route does not work well when the location plan is different. Especially when there are many diverse elite solutions in multi-objective optimization problems. This is also a reason that sequential methods which find a fixed $(\mathbf{z}, \mathbf{y})$ first lack the exploration of the location decision. Therefore, the key to our MOLRP is that we find a way to diversify the location decisions while restricting the optimization of routing to a fixed location plan.

B. Detailed Computational Results on LRP Datasets

The overall performance of our proposed MPGA and SPACO are tested on three well-known Location-Routing Problem (LRP) instance sets. The Barreto's set contains 14 instances, ranging from 50 to 150 nodes; The Prodhon's set contains 30 instances with a range of 20 to 200 nodes; There are 36 instances scaling from 110 to 220 nodes for Tuzun's set. As a supplement to *Section V-B*, we tabulate the detailed computational results in Tables I, II, III, IV, V and VI. The best performer on each instance is shaded.

TABLE I
MEAN AND STANDARD DEVIATION (IN PARENTHESES) OF IGD OBTAINED BY 30 RUNS ON BARRETO'S INSTANCES

Instance	MCACO	MPACO	SPACO	FR-NSGA-II	M-NSGA-II	MPGA
Berreto01	1.11e+02(4.97e+01)	2.61e+02(1.26e+02)	7.76e+01(2.76e+01)	1.24e+02(2.53e+01)	1.50e+02(3.32e+01)	5.44e+01(2.19e+01)
Berreto02	3.84e+02(1.18e+02)	6.91e+02(2.65e+02)	1.62e+02(2.73e+01)	2.27e+02(5.77e+01)	2.40e+02(6.10e+01)	1.23e+02(6.22e+01)
Berreto03	5.18e+02(1.52e+02)	1.11e+03(4.56e+02)	2.26e+02(5.92e+01)	4.34e+02(5.95e+01)	4.60e+02(6.91e+01)	7.46e+01(2.81e+01)
Berreto04	2.46e+06(2.51e+05)	1.56e+06(4.30e+05)	7.76e+05(1.32e+05)	9.23e+05(2.29e+05)	9.69e+05(2.49e+05)	7.90e+05(2.03e+05)
Berreto05	2.01e+07(7.44e+06)	8.55e+07(5.54e+07)	1.39e+07(2.28e+06)	1.27e+07(2.55e+06)	1.38e+07(2.27e+06)	9.39e+06(1.52e+06)
Berreto06	1.05e+03(5.43e+01)	9.36e+02(2.22e+01)	7.51e+02(1.51e+02)	2.00e+02(1.10e+02)	1.65e+02(6.10e+01)	7.37e+02(2.21e+02)
Berreto07	6.04e+02(5.47e+01)	6.08e+02(4.59e+01)	5.04e+02(4.31e+01)	2.18e+02(9.11e+01)	2.53e+02(5.40e+01)	8.89e+01(1.37e+01)
Berreto08	6.21e+02(2.82e+01)	9.39e+02(8.32e+01)	6.86e+02(9.16e+01)	3.50e+02(1.55e+02)	3.47e+02(1.83e+02)	1.77e+02(1.50e+02)
Berreto09	1.83e+03(1.01e+02)	1.77e+03(1.14e+02)	1.63e+03(1.69e+02)	8.27e+02(2.18e+02)	8.84e+02(1.91e+02)	8.42e+02(4.75e+02)
Berreto10	1.47e+03(9.29e+01)	1.48e+03(8.64e+01)	1.33e+03(1.74e+02)	9.50e+02(1.96e+02)	1.02e+03(1.86e+02)	4.66e+02(1.92e+02)
Berreto11	7.76e+01(3.35e+01)	1.33e+02(4.48e+01)	1.41e+02(4.50e+01)	1.35e+02(2.91e+01)	1.56e+02(3.93e+01)	3.39e+01(2.02e+01)
Berreto12	1.78e+03(2.77e+02)	1.65e+03(3.83e+02)	1.61e+03(4.49e+02)	4.40e+02(2.81e+02)	5.59e+02(3.06e+02)	1.30e+03(1.06e+03)
Berreto13	6.93e+03(1.69e+03)	1.17e+04(5.26e+03)	5.53e+03(6.84e+02)	6.45e+03(1.79e+03)	7.42e+03(2.16e+03)	1.10e+03(4.60e+02)
Berreto14	4.46e+05(1.22e+05)	1.19e+06(4.76e+05)	3.55e+05(3.74e+04)	2.01e+05(4.47e+04)	2.30e+05(4.86e+04)	8.77e+04(1.90e+04)

TABLE II
MEAN AND STANDARD DEVIATION (IN PARENTHESES) OF HV OBTAINED BY 30 RUNS ON BARRETO'S INSTANCES

Instance	MCACO	MPACO	SPACO	FR-NSGA-II	M-NSGA-II	MPGA
Berreto01	3.11e+04(3.89e+04)	2.04e+04(3.04e+04)	5.12e+04(2.06e+04)	7.52e+04(1.50e+04)	5.38e+04(1.71e+04)	1.25e+05(2.74e+04)
Berreto02	2.65e+05(2.69e+05)	1.29e+05(1.91e+05)	3.26e+05(1.21e+05)	6.71e+05(1.56e+05)	5.69e+05(1.11e+05)	1.19e+06(2.03e+05)
Berreto03	2.16e+05(3.11e+05)	6.60e+04(1.14e+05)	1.81e+05(8.71e+04)	6.80e+05(1.33e+05)	4.97e+05(1.12e+05)	1.94e+06(1.49e+05)
Berreto04	3.25e+19(3.35e+18)	3.07e+19(8.27e+18)	4.37e+19(1.15e+18)	4.76e+19(1.36e+18)	4.73e+19(1.16e+18)	4.82e+19(1.33e+18)
Berreto05	7.81e+22(2.27e+22)	3.87e+22(5.39e+22)	8.63e+22(7.96e+21)	1.15e+23(9.29e+21)	1.11e+23(8.70e+21)	1.12e+23(8.21e+21)
Berreto06	5.48e+07(2.06e+07)	8.16e+07(2.06e+07)	8.29e+07(2.41e+07)	2.25e+08(1.62e+07)	2.15e+08(1.31e+07)	1.60e+08(2.25e+07)
Berreto07	4.53e+08(7.94e+07)	5.13e+08(5.54e+07)	6.13e+08(9.42e+07)	9.26e+08(7.06e+07)	8.71e+08(4.83e+07)	9.26e+08(3.71e+07)
Berreto08	5.55e+07(2.96e+07)	3.20e+07(2.80e+07)	5.42e+07(3.92e+07)	3.86e+08(2.69e+07)	3.62e+08(2.02e+07)	4.75e+08(3.54e+07)
Berreto09	9.22e+08(3.22e+08)	9.73e+08(5.18e+08)	1.51e+09(2.69e+08)	1.88e+09(3.66e+08)	1.74e+09(4.19e+08)	3.04e+09(3.75e+08)
Berreto10	1.70e+09(4.65e+08)	1.89e+09(7.39e+08)	2.54e+09(5.28e+08)	2.82e+09(6.12e+08)	2.55e+09(4.75e+08)	4.32e+09(4.01e+08)
Berreto11	4.83e+04(4.02e+04)	2.75e+04(3.69e+04)	6.96e+04(1.28e+04)	6.43e+04(1.54e+04)	4.53e+04(1.38e+04)	1.29e+05(1.41e+04)
Berreto12	2.24e+10(3.50e+09)	2.39e+10(4.37e+09)	3.23e+10(4.15e+09)	4.16e+10(3.01e+09)	3.60e+10(4.50e+09)	4.16e+10(2.91e+09)
Berreto13	1.34e+10(1.16e+10)	1.00e+10(1.48e+10)	4.57e+09(2.90e+09)	1.28e+10(4.25e+09)	1.10e+10(4.18e+09)	4.03e+10(6.53e+09)
Berreto14	1.10e+16(7.17e+15)	4.37e+15(6.43e+15)	1.58e+16(2.81e+15)	4.11e+16(6.33e+15)	3.73e+16(6.32e+15)	6.00e+16(3.58e+15)

TABLE III

MEAN AND STANDARD DEVIATION (IN PARENTHESES) OF IGD OBTAINED BY 30 RUNS ON PRODHON'S INSTANCES

Instance	MCACO	MPACO	SPACO	FR-NSGA-II	M-NSGA-II	MPGA
Prodhon01	1.46e+01(6.18e+00)	9.09e+00(2.89e+00)	3.44e+01(2.23e+01)	1.55e+01(1.37e+01)	1.46e+01(4.20e+00)	3.13e+01(1.69e+01)
Prodhon02	2.34e+01(1.08e+01)	3.25e+01(1.00e+01)	5.17e+01(1.99e+01)	5.31e+01(9.64e+00)	6.17e+01(1.12e+01)	5.35e+01(1.21e+01)
Prodhon03	2.80e+01(3.18e+00)	3.24e+01(1.46e+01)	4.19e+01(1.56e+01)	5.80e+00(3.77e+00)	9.44e+00(4.85e+00)	2.83e+01(2.02e+01)
Prodhon04	9.13e+01(1.18e+01)	9.74e+01(1.14e+01)	9.60e+01(2.13e+01)	5.14e+01(1.35e+01)	4.99e+01(8.96e+00)	1.10e+02(2.72e+01)
Prodhon05	9.01e+01(3.26e+01)	1.16e+02(7.11e+01)	4.46e+01(1.39e+01)	3.03e+01(1.22e+01)	4.17e+01(1.77e+01)	6.48e+01(2.62e+01)
Prodhon06	7.93e+01(2.83e+01)	1.29e+02(6.48e+01)	5.32e+01(2.18e+01)	7.40e+01(2.14e+01)	1.00e+02(2.89e+01)	4.46e+01(2.28e+01)
Prodhon07	6.35e+01(2.14e+01)	6.14e+01(3.36e+01)	4.56e+01(1.34e+01)	3.78e+01(1.26e+01)	5.23e+01(1.47e+01)	5.31e+01(2.62e+01)
Prodhon08	6.19e+01(2.39e+01)	1.02e+02(4.88e+01)	5.17e+01(1.13e+01)	7.80e+01(4.30e+01)	1.15e+02(4.23e+01)	3.20e+01(1.61e+01)
Prodhon09	4.74e+01(1.26e+01)	4.61e+01(2.19e+01)	2.35e+01(5.67e+00)	7.34e+01(4.29e+01)	8.28e+01(4.30e+01)	1.51e+01(8.59e+00)
Prodhon10	1.43e+02(3.37e+01)	1.01e+02(3.78e+01)	5.76e+01(1.75e+01)	7.19e+01(1.29e+01)	9.66e+01(2.85e+01)	4.14e+01(2.96e+01)
Prodhon11	1.78e+02(5.02e+01)	1.64e+02(6.55e+01)	8.87e+01(3.24e+01)	6.11e+01(1.09e+01)	7.19e+01(1.09e+01)	6.78e+01(2.62e+01)
Prodhon12	9.06e+01(3.14e+01)	1.22e+02(4.89e+01)	9.42e+01(3.26e+01)	1.10e+02(2.47e+01)	1.28e+02(2.30e+01)	5.86e+01(2.94e+01)
Prodhon13	4.75e+02(1.03e+02)	3.61e+02(2.07e+02)	1.64e+02(3.93e+01)	2.23e+02(2.94e+01)	2.63e+02(3.26e+01)	2.04e+02(6.42e+01)
Prodhon14	1.31e+02(7.60e+01)	2.60e+02(1.75e+02)	1.41e+02(4.26e+01)	2.05e+02(4.22e+01)	2.33e+02(3.34e+01)	1.76e+02(8.60e+01)
Prodhon15	6.81e+02(1.01e+02)	3.72e+02(1.18e+02)	9.57e+01(2.50e+01)	2.77e+02(3.55e+01)	2.84e+02(2.09e+01)	1.37e+02(6.10e+01)
Prodhon16	3.08e+02(8.63e+01)	2.02e+02(1.35e+02)	1.14e+02(5.65e+01)	3.04e+02(2.73e+01)	3.15e+02(2.85e+01)	1.33e+02(9.77e+01)
Prodhon17	4.60e+02(8.60e+01)	2.86e+02(1.48e+02)	1.57e+02(6.59e+01)	3.50e+02(5.04e+01)	3.19e+02(7.38e+01)	2.53e+02(9.81e+01)
Prodhon18	2.50e+02(8.68e+01)	2.38e+02(1.13e+02)	1.21e+02(2.72e+01)	2.45e+02(5.16e+01)	2.41e+02(6.38e+01)	1.83e+02(7.01e+01)
Prodhon19	5.86e+02(1.69e+02)	6.73e+02(2.42e+02)	1.73e+02(5.20e+01)	1.03e+02(3.45e+01)	1.03e+02(3.98e+01)	1.99e+02(8.42e+01)
Prodhon20	2.10e+02(9.80e+01)	5.08e+02(2.84e+02)	3.29e+02(7.65e+01)	3.94e+02(1.02e+02)	3.77e+02(1.08e+02)	1.88e+02(1.29e+02)
Prodhon21	9.12e+02(2.17e+02)	4.26e+02(2.01e+02)	1.11e+02(3.13e+01)	1.64e+02(4.62e+01)	1.76e+02(3.94e+01)	2.19e+02(1.47e+02)
Prodhon22	2.84e+02(1.00e+02)	2.75e+02(1.45e+02)	2.20e+02(2.00e+02)	2.94e+02(6.00e+01)	2.90e+02(6.95e+01)	1.65e+02(1.32e+02)
Prodhon23	7.92e+02(1.50e+02)	7.36e+02(2.13e+02)	1.76e+02(7.50e+01)	1.93e+02(8.15e+01)	1.62e+02(5.27e+01)	2.04e+02(9.44e+01)
Prodhon24	2.00e+02(8.57e+01)	4.00e+02(2.45e+02)	1.63e+02(5.55e+01)	1.80e+02(6.13e+01)	1.85e+02(7.31e+01)	1.19e+02(5.14e+01)
Prodhon25	2.23e+03(3.26e+02)	2.92e+03(8.38e+02)	2.62e+02(1.25e+02)	4.25e+02(1.89e+02)	4.33e+02(1.84e+02)	4.21e+02(1.47e+02)
Prodhon26	1.22e+03(2.25e+02)	1.62e+03(5.50e+02)	6.04e+02(2.72e+02)	5.79e+02(1.61e+02)	5.98e+02(1.50e+02)	4.77e+02(1.89e+02)
Prodhon27	3.26e+03(3.50e+02)	1.78e+03(5.01e+02)	8.63e+02(3.02e+02)	9.54e+02(1.30e+02)	9.51e+02(1.52e+02)	9.68e+02(2.18e+02)
Prodhon28	1.25e+03(2.75e+02)	9.35e+02(3.96e+02)	9.03e+02(2.66e+02)	1.01e+03(2.55e+02)	9.03e+02(2.00e+02)	9.53e+02(3.17e+02)
Prodhon29	2.70e+03(1.62e+02)	2.74e+03(6.15e+02)	1.56e+03(5.60e+02)	1.50e+03(3.58e+02)	1.51e+03(3.57e+02)	1.13e+03(3.29e+02)
Prodhon30	7.88e+02(1.58e+02)	1.05e+03(4.53e+02)	1.59e+03(6.35e+02)	9.78e+02(2.37e+02)	9.90e+02(2.17e+02)	8.89e+02(4.42e+02)

TABLE IV

MEAN AND STANDARD DEVIATION (IN PARENTHESES) OF HV OBTAINED BY 30 RUNS ON PRODHON'S INSTANCES

Instance	MCACO	MPACO	SPACO	FR-NSGA-II	M-NSGA-II	MPGA
Prodhon01	4.45e+03(2.17e+02)	5.03e+03(2.55e+02)	4.34e+03(5.24e+02)	4.84e+03(2.82e+02)	4.50e+03(4.07e+02)	4.25e+03(6.85e+02)
Prodhon02	1.83e+04(1.33e+03)	1.93e+04(3.57e+03)	2.11e+04(2.30e+03)	2.03e+04(1.03e+03)	1.77e+04(1.59e+03)	2.50e+04(1.79e+03)
Prodhon03	2.00e+03(1.24e+02)	2.16e+03(3.15e+02)	2.03e+03(3.89e+02)	2.56e+03(2.74e+02)	2.23e+03(3.08e+02)	1.99e+03(2.81e+02)
Prodhon04	4.50e+04(1.68e+03)	4.71e+04(4.22e+03)	4.26e+04(7.10e+03)	5.92e+04(3.85e+03)	5.64e+04(3.09e+03)	6.48e+04(3.47e+03)
Prodhon05	2.88e+04(1.00e+04)	2.13e+04(2.62e+04)	3.20e+04(9.08e+03)	5.48e+04(5.30e+03)	4.71e+04(8.31e+03)	4.58e+04(1.33e+04)
Prodhon06	3.20e+04(2.17e+04)	2.06e+04(2.98e+04)	4.43e+04(1.35e+04)	5.45e+04(1.06e+04)	4.88e+04(1.38e+04)	7.95e+04(1.63e+04)
Prodhon07	1.09e+04(4.75e+03)	8.89e+03(1.06e+04)	1.07e+04(3.47e+03)	1.52e+04(3.54e+03)	1.19e+04(3.14e+03)	1.40e+04(5.10e+03)
Prodhon08	1.10e+04(8.56e+03)	8.23e+03(1.19e+04)	9.75e+03(6.12e+03)	5.46e+03(4.81e+03)	1.65e+03(3.07e+03)	2.22e+04(5.32e+03)
Prodhon09	1.28e+03(9.24e+02)	1.45e+03(2.01e+03)	2.18e+03(9.73e+02)	4.75e+02(8.64e+02)	1.82e+02(4.13e+02)	4.78e+03(1.26e+03)
Prodhon10	2.07e+03(2.21e+03)	4.68e+03(4.18e+03)	9.11e+03(2.84e+03)	6.13e+03(1.92e+03)	3.66e+03(2.63e+03)	1.26e+04(5.20e+03)
Prodhon11	4.46e+03(4.44e+03)	6.80e+03(8.83e+03)	8.61e+03(4.62e+03)	2.08e+04(3.55e+03)	1.57e+04(2.59e+03)	1.54e+04(4.99e+03)
Prodhon12	1.24e+04(1.37e+04)	1.30e+04(1.88e+04)	1.46e+04(7.94e+03)	3.41e+04(9.09e+03)	2.72e+04(7.58e+03)	4.27e+04(9.74e+03)
Prodhon13	3.00e+05(2.07e+05)	3.15e+05(4.56e+05)	4.70e+05(1.29e+05)	1.46e+05(7.37e+04)	6.82e+04(5.64e+04)	4.13e+05(1.18e+05)
Prodhon14	2.98e+04(4.30e+04)	3.08e+04(4.58e+04)	3.26e+03(7.09e+03)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	1.57e+04(1.39e+04)
Prodhon15	9.99e+03(1.02e+04)	2.46e+04(3.62e+04)	3.41e+04(1.66e+04)	2.64e+03(1.55e+03)	1.08e+03(1.12e+03)	3.78e+04(1.90e+04)
Prodhon16	2.42e+04(3.56e+04)	4.31e+04(6.26e+04)	2.93e+04(2.92e+04)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	5.65e+04(2.79e+04)
Prodhon17	1.65e+05(8.82e+04)	1.64e+05(2.27e+05)	2.56e+05(8.96e+04)	2.75e+05(5.80e+04)	2.17e+05(4.40e+04)	3.20e+05(6.81e+04)
Prodhon18	1.78e+05(1.48e+05)	1.28e+05(1.86e+05)	1.13e+05(4.48e+04)	8.62e+04(5.16e+04)	5.10e+04(3.20e+04)	2.37e+05(4.54e+04)
Prodhon19	2.00e+05(1.78e+05)	1.69e+05(2.47e+05)	1.85e+05(9.95e+04)	5.02e+05(8.96e+04)	4.53e+05(7.52e+04)	6.40e+05(1.12e+05)
Prodhon20	1.22e+06(8.53e+05)	6.77e+05(9.76e+05)	1.09e+06(3.43e+05)	1.24e+06(2.38e+05)	1.14e+06(2.05e+05)	2.43e+06(2.72e+05)
Prodhon21	4.91e+04(7.08e+04)	6.58e+04(1.01e+05)	1.63e+05(4.44e+04)	1.47e+05(6.57e+04)	1.02e+05(5.20e+04)	2.70e+05(7.54e+04)
Prodhon22	5.36e+04(7.74e+04)	5.91e+04(8.88e+04)	5.85e+04(4.99e+04)	3.41e+03(7.47e+03)	5.23e+02(1.77e+03)	1.47e+05(5.83e+04)
Prodhon23	2.20e+05(1.48e+05)	1.51e+05(2.19e+05)	4.39e+05(9.66e+04)	5.05e+05(8.75e+04)	4.44e+05(7.43e+04)	5.57e+05(8.66e+04)
Prodhon24	6.35e+05(4.40e+05)	3.79e+05(5.47e+05)	7.23e+05(1.93e+05)	7.27e+05(1.40e+05)	5.98e+05(1.40e+05)	1.30e+06(1.38e+05)
Prodhon25	3.58e+06(1.87e+06)	1.85e+06(2.66e+06)	3.79e+06(7.84e+05)	5.40e+06(7.50e+05)	5.55e+06(5.29e+05)	6.82e+06(6.72e+05)
Prodhon26	3.19e+06(2.97e+06)	1.75e+06(2.55e+06)	2.48e+06(1.00e+06)	6.94e+05(4.62e+05)	5.01e+05(2.56e+05)	4.92e+06(7.22e+05)
Prodhon27	5.09e+05(6.15e+05)	8.61e+05(1.25e+06)	1.68e+06(4.18e+05)	6.49e+05(2.56e+05)	4.61e+05(1.62e+05)	1.42e+06(3.20e+05)
Prodhon28	9.94e+05(1.22e+06)	1.04e+06(1.53e+06)	8.01e+05(3.68e+05)	1.29e+04(3.03e+04)	0.00e+00(0.00e+00)	1.05e+06(3.87e+05)
Prodhon29	4.40e+05(5.38e+05)	3.15e+05(4.72e+05)	6.57e+05(4.10e+05)	3.34e+04(5.71e+04)	8.33e+03(2.73e+04)	5.93e+05(2.15e+05)
Prodhon30	1.33e+06(1.56e+06)	6.91e+05(1.01e+06)	9.00e+05(4.90e+05)	2.42e+02(1.33e+03)	0.00e+00(0.00e+00)	1.32e+06(3.88e+05)

TABLE V

MEAN AND STANDARD DEVIATION (IN PARENTHESES) OF IGD OBTAINED BY 30 RUNS ON TUZUN'S INSTANCES

Instance	MCACO	MPACO	SPACO	FR-NSGA-II	M-NSGA-II	MPGA
Tuzun01	5.56e+02(2.11e+02)	1.43e+03(7.60e+02)	2.10e+02(6.29e+01)	5.57e+02(9.67e+01)	6.22e+02(8.72e+01)	1.97e+02(8.18e+01)
Tuzun02	3.66e+02(1.55e+02)	1.46e+03(8.12e+02)	1.54e+02(4.48e+01)	2.36e+02(4.84e+01)	2.49e+02(7.10e+01)	1.02e+02(5.72e+01)
Tuzun03	3.34e+02(1.75e+02)	1.33e+03(8.18e+02)	1.18e+02(3.99e+01)	1.99e+02(6.36e+01)	2.02e+02(5.95e+01)	1.40e+02(5.88e+01)
Tuzun04	4.22e+02(1.63e+02)	1.65e+03(8.68e+02)	1.55e+02(4.37e+01)	3.38e+02(8.37e+01)	4.07e+02(8.13e+01)	1.43e+02(8.04e+01)
Tuzun05	2.43e+02(9.41e+01)	6.47e+02(4.05e+02)	1.01e+02(1.89e+01)	2.13e+02(4.90e+01)	2.42e+02(4.22e+01)	6.60e+01(4.35e+01)
Tuzun06	5.12e+02(1.39e+02)	1.00e+03(5.16e+02)	6.35e+01(2.51e+01)	3.01e+02(8.97e+01)	3.27e+02(7.37e+01)	6.21e+01(3.94e+01)
Tuzun07	3.85e+02(8.40e+01)	4.17e+02(2.40e+02)	7.47e+01(2.09e+01)	1.10e+02(2.35e+01)	1.27e+02(2.99e+01)	6.36e+01(3.03e+01)
Tuzun08	9.06e+02(1.58e+02)	8.04e+02(3.74e+02)	1.13e+02(5.91e+01)	1.39e+02(3.03e+01)	1.67e+02(3.55e+01)	1.79e+02(3.80e+01)
Tuzun09	3.18e+02(1.41e+02)	1.00e+03(5.84e+02)	9.70e+01(2.83e+01)	2.95e+02(5.27e+01)	3.15e+02(3.36e+01)	1.23e+02(3.71e+01)
Tuzun10	5.36e+02(1.47e+02)	1.32e+03(6.98e+02)	6.14e+01(1.77e+01)	2.52e+02(1.17e+02)	2.97e+02(1.08e+02)	7.37e+01(5.21e+01)
Tuzun11	5.27e+02(1.37e+02)	8.12e+02(4.31e+02)	7.01e+01(3.36e+01)	1.34e+02(3.86e+01)	1.58e+02(5.67e+01)	1.33e+02(8.72e+01)
Tuzun12	5.92e+02(1.46e+02)	1.19e+03(6.46e+02)	9.72e+01(5.56e+01)	1.02e+02(4.78e+01)	1.23e+02(5.47e+01)	1.07e+02(7.05e+01)
Tuzun13	5.43e+02(3.11e+02)	3.33e+03(2.17e+03)	2.00e+02(5.46e+01)	4.99e+02(1.09e+02)	6.03e+02(1.31e+02)	1.78e+02(5.64e+01)
Tuzun14	6.73e+02(3.78e+02)	4.09e+03(2.45e+03)	1.63e+02(3.06e+01)	1.78e+02(5.68e+01)	1.82e+02(4.37e+01)	1.35e+02(6.96e+01)
Tuzun15	6.36e+02(3.47e+02)	3.27e+03(2.06e+03)	1.82e+02(6.63e+01)	5.30e+02(1.02e+02)	6.40e+02(8.45e+01)	2.04e+02(4.71e+01)
Tuzun16	7.28e+02(3.86e+02)	4.25e+03(2.51e+03)	1.79e+02(2.93e+01)	2.58e+02(6.31e+01)	2.99e+02(9.29e+01)	1.35e+02(4.33e+01)
Tuzun17	6.30e+02(2.85e+02)	2.22e+03(1.41e+03)	1.15e+02(4.63e+01)	5.56e+02(8.61e+01)	5.79e+02(8.58e+01)	1.44e+02(6.59e+01)
Tuzun18	9.20e+02(3.03e+02)	2.36e+03(1.37e+03)	1.34e+02(2.03e+01)	4.38e+02(1.26e+02)	5.70e+02(1.18e+02)	1.11e+02(4.12e+01)
Tuzun19	8.61e+02(2.09e+02)	1.58e+03(8.94e+02)	1.01e+02(2.87e+01)	4.94e+02(4.87e+01)	5.36e+02(5.47e+01)	3.26e+02(6.19e+01)
Tuzun20	1.69e+03(2.14e+02)	2.27e+03(1.26e+03)	4.66e+01(1.52e+01)	2.34e+02(4.40e+01)	2.39e+02(4.64e+01)	1.04e+02(3.98e+01)
Tuzun21	5.25e+02(2.60e+02)	2.53e+03(1.64e+03)	1.37e+02(4.29e+01)	3.22e+02(7.10e+01)	3.78e+02(8.00e+01)	1.78e+02(6.49e+01)
Tuzun22	9.94e+02(3.13e+02)	3.92e+03(2.16e+03)	1.32e+02(2.62e+01)	3.06e+02(7.17e+01)	3.74e+02(8.82e+01)	1.23e+02(4.89e+01)
Tuzun23	7.76e+02(2.51e+02)	2.11e+03(1.31e+03)	8.69e+01(4.87e+01)	2.46e+02(7.33e+01)	2.76e+02(6.76e+01)	3.02e+02(7.40e+01)
Tuzun24	1.41e+03(2.75e+02)	2.94e+03(1.70e+03)	1.23e+02(8.97e+01)	1.09e+02(5.46e+01)	1.34e+02(5.33e+01)	3.51e+01(1.77e+01)
Tuzun25	6.17e+02(3.03e+02)	2.39e+03(1.43e+03)	1.58e+02(3.49e+01)	6.28e+02(8.67e+01)	6.84e+02(1.33e+02)	1.55e+02(6.11e+01)
Tuzun26	6.39e+02(2.86e+02)	3.00e+03(1.64e+03)	1.61e+02(3.44e+01)	2.54e+02(7.22e+01)	3.45e+02(9.91e+01)	1.64e+02(9.00e+01)
Tuzun27	7.11e+02(3.14e+02)	2.45e+03(1.52e+03)	1.70e+02(9.21e+01)	6.12e+02(1.37e+02)	6.84e+02(1.43e+02)	2.03e+02(6.72e+01)
Tuzun28	7.38e+02(3.15e+02)	3.14e+03(1.65e+03)	1.97e+02(3.98e+01)	4.30e+02(1.33e+02)	5.03e+02(1.57e+02)	1.71e+02(9.11e+01)
Tuzun29	6.45e+02(2.36e+02)	1.36e+03(8.13e+02)	6.99e+01(1.95e+01)	4.20e+02(1.05e+02)	4.90e+02(1.05e+02)	1.23e+02(6.31e+01)
Tuzun30	9.40e+02(2.42e+02)	1.80e+03(8.97e+02)	1.13e+02(2.40e+01)	5.76e+02(1.36e+02)	6.24e+02(9.54e+01)	1.71e+02(8.69e+01)
Tuzun31	6.30e+02(1.72e+02)	9.54e+02(6.22e+02)	6.60e+01(2.37e+01)	1.32e+02(2.89e+01)	1.65e+02(3.00e+01)	5.28e+01(2.60e+01)
Tuzun32	8.99e+02(1.65e+02)	1.02e+03(5.99e+02)	4.51e+01(1.55e+01)	2.94e+02(7.04e+01)	3.35e+02(4.99e+01)	5.20e+01(2.15e+01)
Tuzun33	8.12e+02(2.40e+02)	1.81e+03(1.03e+03)	9.78e+01(5.53e+01)	6.94e+02(1.27e+02)	8.03e+02(1.53e+02)	1.45e+02(9.13e+01)
Tuzun34	7.06e+02(2.38e+02)	1.98e+03(1.15e+03)	1.44e+02(3.84e+01)	2.36e+02(5.22e+01)	2.21e+02(5.33e+01)	1.30e+02(4.79e+01)
Tuzun35	8.42e+02(2.01e+02)	1.07e+03(7.03e+02)	9.12e+01(4.84e+01)	3.52e+02(6.58e+01)	4.49e+02(7.51e+01)	3.26e+02(9.66e+01)
Tuzun36	9.99e+02(2.57e+02)	2.10e+03(1.09e+03)	6.47e+01(3.98e+01)	6.88e+01(2.24e+01)	6.82e+01(1.10e+01)	7.42e+01(2.38e+01)

TABLE VI

MEAN AND STANDARD DEVIATION (IN PARENTHESES) OF HV OBTAINED BY 30 RUNS ON TUZUN'S INSTANCES

Instance	MCACO	MPACO	SPACO	FR-NSGA-II	M-NSGA-II	MPGA
Tuzun01	2.51e+05(3.51e+05)	1.59e+05(2.48e+05)	1.08e+05(2.30e+05)	2.72e+05(1.12e+05)	1.75e+05(7.36e+04)	9.01e+05(1.83e+05)
Tuzun02	9.26e+05(1.04e+06)	4.24e+05(6.54e+05)	1.71e+06(5.12e+05)	2.52e+06(3.79e+05)	2.21e+06(4.79e+05)	3.92e+06(5.35e+05)
Tuzun03	2.37e+05(3.39e+05)	1.49e+05(2.36e+05)	2.60e+05(1.92e+05)	3.60e+05(1.18e+05)	2.43e+05(9.81e+04)	7.54e+05(1.55e+05)
Tuzun04	1.16e+06(1.04e+06)	3.96e+05(5.92e+05)	1.42e+06(4.44e+05)	2.50e+06(4.59e+05)	2.03e+06(3.76e+05)	4.23e+06(3.95e+05)
Tuzun05	7.70e+04(1.04e+05)	7.01e+04(1.06e+05)	1.27e+05(7.67e+04)	1.24e+05(3.47e+04)	9.49e+04(3.17e+04)	4.53e+05(9.62e+04)
Tuzun06	3.10e+03(5.48e+03)	3.46e+03(8.79e+03)	4.78e+04(3.36e+04)	1.11e+04(1.42e+04)	6.61e+03(1.02e+04)	2.61e+05(5.56e+04)
Tuzun07	4.37e+03(8.85e+03)	1.54e+04(2.36e+04)	4.35e+04(2.09e+04)	2.17e+04(1.38e+04)	1.34e+04(1.15e+04)	1.08e+05(3.65e+04)
Tuzun08	0.00e+00(0.00e+00)	2.30e+03(5.33e+03)	2.55e+04(1.96e+04)	8.72e+03(4.60e+03)	4.75e+03(4.25e+03)	2.32e+04(1.28e+04)
Tuzun09	1.25e+05(1.60e+05)	7.54e+04(1.23e+05)	1.31e+05(8.42e+04)	2.61e+05(5.16e+04)	2.17e+05(4.73e+04)	5.76e+05(9.64e+04)
Tuzun10	1.32e+03(6.02e+03)	3.76e+03(1.22e+04)	2.47e+05(9.32e+04)	8.14e+04(7.40e+04)	4.60e+04(5.99e+04)	4.02e+05(1.47e+05)
Tuzun11	3.78e+04(5.25e+04)	7.06e+04(1.05e+05)	2.96e+05(7.73e+04)	2.05e+05(4.05e+04)	1.60e+05(4.02e+04)	3.01e+05(1.13e+05)
Tuzun12	0.00e+00(0.00e+00)	3.48e+03(8.79e+03)	3.78e+04(3.15e+04)	1.66e+05(2.85e+04)	1.41e+05(2.86e+04)	1.79e+05(5.59e+04)
Tuzun13	9.12e+05(1.30e+06)	3.86e+05(6.10e+05)	2.46e+05(2.44e+05)	1.29e+05(1.10e+05)	7.11e+04(9.42e+04)	1.57e+06(3.61e+05)
Tuzun14	7.68e+05(1.11e+06)	9.79e+04(1.87e+05)	3.63e+05(3.08e+05)	1.41e+06(4.13e+05)	1.02e+06(3.99e+05)	2.90e+06(8.55e+05)
Tuzun15	1.04e+06(1.51e+06)	4.23e+05(6.71e+05)	3.50e+05(2.72e+05)	2.28e+05(1.78e+05)	5.46e+04(7.10e+04)	2.16e+06(4.97e+05)
Tuzun16	1.16e+06(1.68e+06)	1.64e+05(2.47e+05)	6.41e+05(4.77e+05)	1.14e+06(4.68e+05)	9.21e+05(3.98e+05)	3.92e+06(8.22e+05)
Tuzun17	1.31e+05(2.13e+05)	8.71e+04(1.41e+05)	7.71e+04(1.17e+05)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	3.03e+05(1.67e+05)
Tuzun18	3.25e+05(4.75e+05)	1.97e+05(3.23e+05)	1.17e+06(4.00e+05)	6.44e+05(2.97e+05)	3.65e+05(2.58e+05)	3.09e+06(4.50e+05)
Tuzun19	1.15e+05(1.83e+05)	1.75e+05(2.63e+05)	6.21e+05(1.86e+05)	3.35e+04(3.38e+04)	1.99e+04(2.21e+04)	3.03e+05(9.11e+04)
Tuzun20	0.00e+00(0.00e+00)	3.91e+03(8.22e+03)	1.28e+05(5.51e+04)	2.84e+03(6.04e+03)	4.35e+02(2.38e+03)	1.77e+05(4.61e+04)
Tuzun21	4.60e+05(6.65e+05)	2.60e+05(3.92e+05)	2.84e+05(3.52e+05)	1.63e+05(1.30e+05)	7.13e+04(7.58e+04)	1.16e+06(3.73e+05)
Tuzun22	3.51e+05(5.13e+05)	4.33e+04(1.12e+05)	1.04e+06(6.22e+05)	1.64e+06(4.79e+05)	1.23e+06(3.95e+05)	3.98e+06(5.83e+05)
Tuzun23	2.40e+05(3.55e+05)	1.98e+05(3.06e+05)	4.77e+05(1.48e+05)	5.37e+05(2.35e+05)	4.17e+05(2.06e+05)	4.91e+05(2.69e+05)
Tuzun24	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	3.31e+03(1.06e+04)	2.59e+03(5.38e+03)	2.89e+02(1.58e+03)	9.00e+04(2.62e+04)
Tuzun25	1.23e+06(1.70e+06)	6.34e+05(9.39e+05)	8.86e+05(5.23e+05)	5.63e+05(2.59e+05)	3.41e+05(2.66e+05)	3.80e+06(7.92e+05)
Tuzun26	5.21e+05(7.62e+05)	1.66e+04(4.46e+04)	5.71e+05(4.23e+05)	1.42e+06(2.77e+05)	9.13e+05(3.84e+05)	2.69e+06(4.42e+05)
Tuzun27	1.63e+05(2.66e+05)	1.01e+05(1.70e+05)	1.34e+05(1.38e+05)	1.74e+03(4.40e+03)	2.12e+03(1.16e+04)	6.29e+05(2.77e+05)
Tuzun28	1.04e+06(1.44e+06)	1.61e+05(3.14e+05)	5.45e+05(4.88e+05)	2.11e+06(4.56e+05)	1.61e+06(5.11e+05)	4.37e+06(5.22e+05)
Tuzun29	1.54e+05(2.23e+05)	1.46e+05(2.13e+05)	3.86e+05(1.48e+05)	1.32e+05(7.34e+04)	8.40e+04(5.54e+04)	7.03e+05(2.32e+05)
Tuzun30	2.79e+04(4.39e+04)	2.36e+04(4.40e+04)	2.56e+05(2.04e+05)	7.66e+04(7.67e+04)	3.63e+04(3.25e+04)	1.04e+06(3.01e+05)
Tuzun31	3.92e+03(8.65e+03)	3.34e+04(5.19e+04)	5.57e+04(3.53e+04)	2.69e+04(1.54e+04)	1.26e+04(8.28e+03)	1.59e+05(3.72e+04)
Tuzun32	0.00e+00(0.00e+00)	7.53e+03(1.32e+04)	3.36e+04(2.59e+04)	8.25e-01(4.52e+00)	0.00e+00(0.00e+00)	5.74e+04(2.34e+04)
Tuzun33	1.77e+05(2.51e+05)	2.28e+05(3.49e+05)	5.01e+05(1.91e+05)	1.51e+05(1.17e+05)	6.62e+04(7.28e+04)	1.28e+06(3.71e+05)
Tuzun34	2.94e+05(4.20e+05)	2.38e+05(3.56e+05)	7.33e+05(2.62e+05)	1.56e+06(1.77e+05)	1.34e+06(2.00e+05)	2.39e+06(2.36e+05)
Tuzun35	2.06e+00(1.13e+01)	4.64e+03(8.93e+03)	4.41e+03(6.82e+03)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	3.44e+02(1.62e+03)
Tuzun36	1.74e+00(9.52e+00)	0.00e+00(0.00e+00)	4.45e+04(4.08e+04)	6.97e+04(1.92e+04)	4.91e+04(1.73e+04)	1.16e+05(3.02e+04)

C. Comparison of Different Mutation Operators of MPGA

We present the detailed flow of the mutation operators of MPGA here as a supplement to *Section III-D*.

The flow of "insert" operator is presented in **Algorithm 1**. It first randomly selects a customer i. Then find the satellite depots and vehicles that have extra capacity to cover i's stock. Then we can know all the feasible positions L to insert i. We choose the position between $(l, l^{'})$ where the newly added visit causes minimum extra travel distance according to:

$$(l, l^{'}) = \arg\min_{(l,l^{'})}(d_{li} + d_{il'} - d_{ll'}) \tag{1}$$

$$\text{s.t.} \quad x_{ll'}^{k} = 1, k \in S^{avail}, l, l^{'} \in V_1 \cup D^{avail} \tag{2}$$

$$i \in C_2. \tag{3}$$

This insert method is the same with the method described in *Section III-C*.

Algorithm 1 The "insert" mutation operation

```
1: for each solution R in Suboffspring do
2:     i ← chooseCustomer(R)
3:     D^avail ← {j | load_j^depot + q_i ≤ a_j}, j ∈ V_3
4:     S^avail ← {k | load_k^vehicle + q_i ≤ h}, k ∈ K
5:     L ← {(l, l') | x^k_{l,l'} = 1, y_lj = 1, k ∈ S^avail, j ∈ D^avail}
6:     get (l, l') according to Eq. (1 − 3)
7:     insert i between (l, l')
8: end for
```

The flow of "swap" operator is presented in **Algorithm 2**. It goes as follows. We first calculate the membership of customers to the opened depots according to

$$mem_{ij} = \frac{1}{\sum_{j' \in V_3}(\frac{d_{ij}}{d_{ij'}})^2}, i \in V_1, j \in V_3. \tag{4}$$

Then we can identify the ideal satellite depot D_i^{ideal} who has the highest membership value of i, and its current assigned satellite depot D_i^{cur}. Afterwards, for the customers in C^s, whose current satellite depot is not its ideal satellite depot, we take swap operation to find a better match. Specifically, we take the membership value of customer i to its current depot as a measure of satisfaction. The lower satisfaction of a customer is, the more necessary we should rematch it to a better satellite depot. We exchange the positions in the chromosome of customers p and q (inter-sub-route swap), if they happen to be assigned to each other's ideal depot, and also in condition that the depot capacity constraint will not be violated. If all the customers are well-assigned to their ideal satellite depots, we will randomly swap two customers in the same sub-route (intra-sub-route swap), which obviously will not violate any capacity constraints.

Algorithm 2 The "swap" mutation operation

for each solution R in *Suboffspring* **do**
  $mem_{ij} \leftarrow \text{calcMem}(\mathbf{z}, d_{ij}), i \in V_1, j \in V_3$
  $D_i^{ideal} \leftarrow \arg\max_j \{mem_{ij}\}, i \in V_1, j \in V_3$
  $D_i^{cur} \leftarrow j \in \{j \mid y_{ij} = 1\}$
  $C^s \leftarrow \{i \mid D_i^{cur} \neq D_i^{ideal}\}$
  sort C^s by ascending order of $\{mem_{ij} \mid y_{ij} = 1\}$
  if $|C^s| \geq 2$ **then**
    for p in C^s **do**
      $q \leftarrow q \in \{q \mid D_p^{cur} = D_q^{ideal} \& D_q^{cur} = D_p^{ideal}\}$
      if is feasible swap **then**
        change the positions of (p, q)
        break
      end if
    end for
  else
    change the positions of (p, q)
  end if
end for

For the "reverse" operator, as shown in **Algorithm 3**, we randomly select a sub-route, and set the opposite customer visiting sequence to it. The "reverse" operation is done within a sub-route, so no capacity constraint will be violated.

Algorithm 3 The "reverse" mutation operation

for each solution R in *Suboffspring* **do**
  $S_k \leftarrow \text{chooseSubroute}(R)$
  reverse the visiting sequence of S_k
end for

We investigate into the efficiency of these mutation operators. The different versions of MPGA with "insert", "swap" and "reverse" operators are denoted as MPGA-m1, MPGA-m2 and MPGA-m3, respectively. Finally, we design the MPGA-m4 to randomly use one of the three operators with equal probability at each mutation operation. These versions are applied to our MOLRP with three datasets. The results are listed in Table VII, Table VIII and Table IX, respectively. The best performer on each instance is shaded. We can see from the experiment results that the "insert" operator takes the overall leading position on both IGD and HV metrics. Therefore, we determine to use the "insert" mutation operator in our MPGA.

TABLE VII

MEAN AND STANDARD DEVIATION (IN PARENTHESES) OF IGD AND HV OBTAINED BY 30 RUNS ON BARRETO'S INSTANCES. MPGA-M1 USES THE 'INSERT' OPERATOR; MPGA-M2 USES THE 'SWAP' OPERATOR; MPGA-M3 USES THE 'REVERSE' OPERATOR; MPGA-M4 RANDOMLY USES THE THREE OPERATORS WITH EQUAL PROBABILITY.

Instance	MPGA-m1 (IGD)	MPGA-m2 (IGD)	MPGA-m3 (IGD)	MPGA-m4 (IGD)	MPGA-m1 (HV)	MPGA-m2 (HV)	MPGA-m3 (HV)	MPGA-m4 (HV)
Berreto01	5.44e+01(2.19e+01)	8.79e+01(1.93e+01)	9.02e+01(2.50e+01)	5.76e+01(1.82e+01)	1.25e+05(2.74e+04)	5.17e+04(3.56e+04)	3.92e+04(2.69e+04)	1.09e+05(2.55e+04)
Berreto02	1.23e+02(6.22e+01)	3.54e+02(1.02e+02)	5.84e+02(1.97e+02)	1.48e+02(6.10e+01)	1.19e+06(2.03e+05)	2.17e+05(1.23e+05)	4.31e+04(7.95e+04)	1.01e+06(1.64e+05)
Berreto03	7.46e+01(2.81e+01)	4.71e+02(1.56e+02)	6.46e+02(2.85e+02)	9.95e+01(3.85e+01)	1.94e+06(1.49e+05)	2.84e+05(1.12e+05)	4.28e+04(1.18e+05)	1.67e+06(2.51e+05)
Berreto04	7.90e+05(2.03e+05)	1.20e+06(3.11e+05)	1.34e+06(2.13e+05)	8.79e+05(2.03e+05)	4.82e+19(1.33e+18)	4.41e+19(1.89e+18)	4.25e+19(3.18e+18)	4.65e+19(1.78e+18)
Berreto05	9.39e+06(1.52e+06)	1.22e+07(1.35e+06)	3.51e+07(1.31e+07)	1.22e+07(1.49e+06)	1.12e+23(8.21e+21)	9.71e+22(7.53e+21)	4.15e+22(1.41e+22)	8.75e+22(1.26e+22)
Berreto06	7.37e+02(2.21e+02)	5.75e+02(2.97e+02)	7.01e+02(3.59e+02)	5.84e+02(3.10e+02)	1.60e+08(2.25e+07)	1.42e+08(3.77e+07)	1.13e+08(4.12e+07)	1.76e+08(3.00e+07)
Berreto07	8.89e+01(1.37e+01)	1.05e+02(2.20e+01)	1.31e+02(3.53e+01)	8.34e+01(1.14e+01)	9.26e+08(3.71e+07)	9.11e+08(3.26e+07)	8.60e+08(4.32e+07)	9.37e+08(2.53e+07)
Berreto08	1.77e+02(1.50e+02)	2.07e+02(8.20e+01)	4.49e+02(2.17e+02)	1.60e+02(1.11e+02)	4.75e+08(3.54e+07)	4.08e+08(4.26e+07)	3.44e+08(6.48e+07)	4.86e+08(2.91e+07)
Berreto09	8.42e+02(4.75e+02)	1.18e+03(3.38e+02)	1.50e+03(3.99e+02)	9.02e+02(3.43e+02)	3.04e+09(3.75e+08)	2.43e+09(3.81e+08)	2.61e+09(6.11e+08)	3.05e+09(4.27e+08)
Berreto10	4.66e+02(1.92e+02)	6.63e+02(1.66e+02)	7.44e+02(1.55e+02)	4.86e+02(1.95e+02)	4.32e+09(4.01e+08)	3.25e+09(4.53e+08)	3.55e+09(4.47e+08)	4.26e+09(6.80e+08)
Berreto11	3.39e+01(2.02e+01)	1.17e+02(2.86e+01)	1.22e+02(3.28e+01)	5.33e+01(3.55e+01)	1.29e+05(1.41e+04)	3.14e+04(2.42e+04)	3.33e+04(2.75e+04)	1.24e+05(1.43e+04)
Berreto12	1.30e+03(1.06e+03)	1.22e+03(7.46e+02)	1.34e+03(8.49e+02)	8.54e+02(7.53e+02)	4.16e+10(2.91e+09)	3.47e+10(3.19e+09)	3.05e+10(5.10e+09)	4.20e+10(3.05e+09)
Berreto13	1.10e+03(4.60e+02)	7.83e+03(3.77e+03)	9.74e+03(2.40e+03)	1.99e+03(1.32e+03)	4.03e+10(6.53e+09)	2.32e+09(5.36e+09)	7.03e+07(3.85e+08)	3.15e+10(1.00e+10)
Berreto14	8.77e+04(1.90e+04)	1.83e+05(3.24e+04)	5.98e+05(7.62e+04)	9.09e+04(2.33e+04)	6.00e+16(3.58e+15)	2.88e+16(5.99e+15)	3.04e+15(2.25e+15)	5.76e+16(3.50e+15)

TABLE VIII

MEAN AND STANDARD DEVIATION (IN PARENTHESES) OF IGD AND HV OBTAINED BY 30 RUNS ON PRODHON'S INSTANCES. MPGA-M1 USES THE 'INSERT' OPERATOR; MPGA-M2 USES THE 'SWAP' OPERATOR; MPGA-M3 USES THE 'REVERSE' OPERATOR; MPGA-M4 RANDOMLY USES THE THREE OPERATORS WITH EQUAL PROBABILITY.

Instance	MPGA-m1 (IGD)	MPGA-m2 (IGD)	MPGA-m3 (IGD)	MPGA-m4 (IGD)	MPGA-m1 (HV)	MPGA-m2 (HV)	MPGA-m3 (HV)	MPGA-m4 (HV)
Prodhon01	3.13e+01(1.69e+01)	3.65e+01(1.50e+01)	3.41e+01(1.59e+01)	2.89e+01(1.51e+01)	4.25e+03(6.85e+02)	3.62e+03(1.12e+03)	3.97e+03(1.07e+03)	4.59e+03(8.99e+02)
Prodhon02	5.35e+01(1.21e+01)	5.71e+01(1.42e+01)	6.26e+01(1.66e+01)	5.54e+01(1.31e+01)	2.50e+04(1.79e+03)	2.42e+04(2.51e+03)	2.40e+04(2.59e+03)	2.63e+04(2.12e+03)
Prodhon03	2.83e+01(2.02e+01)	4.84e+01(2.40e+01)	4.36e+01(2.24e+01)	2.44e+01(1.52e+01)	1.99e+03(2.81e+02)	1.68e+03(3.67e+02)	1.73e+03(3.11e+02)	1.98e+03(3.23e+02)
Prodhon04	1.10e+02(2.72e+01)	1.16e+02(3.77e+01)	1.40e+02(3.38e+01)	1.19e+02(2.64e+01)	6.48e+04(3.47e+03)	6.11e+04(3.72e+03)	6.08e+04(5.02e+03)	6.66e+04(2.50e+03)
Prodhon05	6.48e+01(2.62e+01)	1.19e+02(3.25e+01)	1.91e+02(5.36e+01)	7.39e+01(2.51e+01)	4.58e+04(1.33e+04)	2.17e+04(7.24e+03)	6.49e+03(6.39e+03)	3.94e+04(1.01e+04)
Prodhon06	4.46e+01(2.28e+01)	1.09e+02(3.69e+01)	1.21e+02(4.23e+01)	5.39e+01(2.72e+01)	7.95e+04(1.63e+04)	3.69e+04(2.11e+04)	2.57e+04(1.81e+04)	7.43e+04(1.36e+04)
Prodhon07	5.31e+01(2.62e+01)	8.35e+01(1.12e+01)	1.16e+02(2.65e+01)	6.65e+01(2.77e+01)	1.40e+04(5.10e+03)	3.58e+03(2.98e+03)	1.27e+03(2.08e+03)	1.08e+04(6.13e+03)
Prodhon08	3.20e+01(1.61e+01)	9.19e+01(3.27e+01)	1.10e+02(3.90e+01)	5.13e+01(2.72e+01)	2.22e+04(5.32e+03)	7.64e+03(6.12e+03)	5.66e+03(5.81e+03)	1.78e+04(7.10e+03)
Prodhon09	1.51e+01(8.59e+00)	7.24e+01(4.18e+01)	9.36e+01(4.63e+01)	1.98e+01(1.63e+01)	4.78e+03(1.26e+03)	1.07e+03(1.08e+03)	6.92e+02(9.74e+02)	4.45e+03(1.41e+03)
Prodhon10	4.14e+01(2.96e+01)	7.93e+01(5.36e+01)	8.89e+01(5.40e+01)	4.99e+01(3.89e+01)	1.26e+04(5.20e+03)	7.09e+03(6.42e+03)	5.06e+03(6.25e+03)	1.17e+04(6.25e+03)
Prodhon11	6.78e+01(2.62e+01)	1.60e+02(4.94e+01)	2.32e+02(5.06e+01)	8.73e+01(3.99e+01)	1.54e+04(4.99e+03)	3.19e+03(2.92e+03)	6.40e+02(1.66e+03)	1.38e+04(5.84e+03)
Prodhon12	5.86e+01(2.94e+01)	1.13e+02(3.11e+01)	1.44e+02(4.33e+01)	5.98e+01(1.97e+01)	4.27e+04(9.74e+03)	8.03e+03(6.91e+03)	5.74e+03(6.98e+03)	4.24e+04(1.13e+04)
Prodhon13	2.04e+02(6.42e+01)	3.14e+02(7.13e+01)	4.20e+02(9.58e+01)	2.28e+02(6.01e+01)	4.13e+05(1.18e+05)	3.61e+04(7.82e+04)	3.81e+02(1.58e+03)	2.57e+05(1.80e+05)
Prodhon14	1.76e+02(8.60e+01)	2.82e+02(4.52e+01)	2.96e+02(3.45e+01)	1.98e+02(6.45e+01)	1.57e+04(1.39e+04)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	2.70e+03(5.97e+03)
Prodhon15	1.37e+02(6.10e+01)	2.77e+02(4.16e+01)	3.62e+02(4.96e+01)	2.00e+02(5.06e+01)	3.78e+04(1.90e+04)	5.07e+01(1.65e+02)	0.00e+00(0.00e+00)	1.50e+04(1.30e+04)
Prodhon16	1.33e+02(9.77e+01)	2.73e+02(8.84e+01)	3.29e+02(4.66e+01)	1.98e+02(1.33e+02)	5.65e+04(2.79e+04)	1.43e+02(6.65e+02)	0.00e+00(0.00e+00)	4.15e+04(2.38e+04)
Prodhon17	2.53e+02(9.81e+01)	3.26e+02(2.30e+01)	4.24e+02(2.76e+01)	3.21e+02(8.26e+01)	3.20e+05(6.81e+04)	5.08e+04(1.82e+04)	6.79e+02(1.62e+03)	2.34e+05(8.09e+04)
Prodhon18	1.83e+02(7.01e+01)	2.87e+02(6.27e+01)	2.98e+02(5.51e+01)	2.29e+02(5.61e+01)	2.37e+05(4.54e+04)	5.60e+03(1.33e+04)	0.00e+00(0.00e+00)	1.89e+05(5.94e+04)
Prodhon19	1.99e+02(8.42e+01)	2.23e+02(3.23e+01)	2.07e+02(2.39e+01)	2.41e+02(8.45e+01)	6.40e+05(1.12e+05)	1.67e+05(3.43e+04)	1.93e+03(4.07e+03)	4.77e+05(1.19e+05)
Prodhon20	1.88e+02(1.29e+02)	4.32e+02(1.76e+02)	6.11e+02(6.57e+01)	3.27e+02(1.69e+02)	2.43e+06(2.72e+05)	8.23e+05(1.61e+05)	1.85e+04(7.86e+04)	1.96e+06(2.99e+05)
Prodhon21	2.19e+02(1.47e+02)	3.00e+02(5.19e+01)	3.25e+02(3.28e+01)	2.39e+02(1.06e+02)	2.70e+05(7.54e+04)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	1.59e+05(7.41e+04)
Prodhon22	1.65e+02(1.32e+02)	4.65e+02(6.11e+01)	5.32e+02(6.70e+01)	2.44e+02(1.37e+02)	1.47e+05(5.83e+04)	3.92e+01(1.50e+02)	0.00e+00(0.00e+00)	9.24e+04(3.32e+04)
Prodhon23	2.04e+02(9.44e+01)	2.38e+02(4.08e+01)	2.98e+02(3.01e+01)	2.52e+02(7.73e+01)	5.57e+05(8.66e+04)	1.50e+05(2.52e+04)	3.71e+02(1.35e+03)	4.83e+05(8.48e+04)
Prodhon24	1.19e+02(5.14e+01)	2.52e+02(9.68e+01)	5.06e+02(6.96e+01)	1.75e+02(7.98e+01)	1.30e+06(1.38e+05)	3.00e+05(6.53e+04)	6.98e+03(2.58e+04)	1.14e+06(1.44e+05)
Prodhon25	4.21e+02(1.47e+02)	3.81e+02(7.62e+01)	4.55e+02(4.83e+01)	5.14e+02(2.16e+02)	6.82e+06(6.72e+05)	2.94e+06(3.31e+05)	4.27e+05(1.67e+05)	4.22e+06(8.51e+05)
Prodhon26	4.77e+02(1.89e+02)	6.20e+02(8.81e+01)	9.51e+02(1.04e+02)	5.67e+02(1.17e+02)	4.92e+06(7.22e+05)	2.17e+05(1.48e+05)	0.00e+00(0.00e+00)	2.63e+06(7.45e+05)
Prodhon27	9.68e+02(2.18e+02)	1.14e+03(1.91e+02)	1.11e+03(1.68e+02)	1.15e+03(3.03e+02)	1.42e+06(3.20e+05)	1.97e+03(7.53e+03)	0.00e+00(0.00e+00)	5.25e+05(3.07e+05)
Prodhon28	9.53e+02(3.17e+02)	1.02e+03(1.58e+02)	1.01e+03(1.58e+02)	1.16e+03(3.31e+02)	1.05e+06(3.87e+05)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	4.63e+05(2.66e+05)
Prodhon29	1.13e+03(3.29e+02)	1.14e+03(2.66e+02)	1.05e+03(2.18e+02)	1.11e+03(3.65e+02)	5.93e+05(2.15e+05)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	1.24e+05(1.37e+05)
Prodhon30	8.89e+02(4.42e+02)	7.80e+02(2.23e+02)	8.42e+02(9.11e+01)	1.06e+03(4.52e+02)	1.32e+06(3.88e+05)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	2.09e+05(1.77e+05)

TABLE IX

MEAN AND STANDARD DEVIATION (IN PARENTHESES) OF IGD AND HV OBTAINED BY 30 RUNS ON TUZUN'S INSTANCES. MPGA-M1 USES THE 'INSERT' OPERATOR; MPGA-M2 USES THE 'SWAP' OPERATOR; MPGA-M3 USES THE 'REVERSE' OPERATOR; MPGA-M4 RANDOMLY USES THE THREE OPERATORS WITH EQUAL PROBABILITY.

Instance	MPGA-m1 (IGD)	MPGA-m2 (IGD)	MPGA-m3 (IGD)	MPGA-m4 (IGD)	MPGA-m1 (HV)	MPGA-m2 (HV)	MPGA-m3 (HV)	MPGA-m4 (HV)
Tuzun01	1.97e+02(8.18e+01)	6.89e+02(1.11e+02)	1.35e+03(2.70e+02)	2.00e+02(9.78e+01)	9.01e+05(1.83e+05)	1.87e+04(2.84e+04)	6.71e+03(3.66e+04)	7.76e+05(2.49e+05)
Tuzun02	1.02e+02(5.72e+01)	4.08e+02(9.81e+01)	1.08e+03(8.02e+01)	1.20e+02(3.29e+01)	3.92e+06(5.35e+05)	9.53e+05(2.37e+05)	0.00e+00(0.00e+00)	3.61e+06(5.09e+05)
Tuzun03	1.40e+02(5.88e+01)	5.64e+02(1.32e+02)	1.04e+03(2.13e+02)	1.40e+02(5.91e+01)	7.54e+05(1.55e+05)	3.54e+04(3.63e+04)	0.00e+00(0.00e+00)	6.99e+05(1.81e+05)
Tuzun04	1.43e+02(8.04e+01)	5.09e+02(9.46e+01)	1.19e+03(5.78e+01)	1.66e+02(5.60e+01)	4.23e+06(3.95e+05)	1.42e+06(1.67e+05)	0.00e+00(0.00e+00)	3.86e+06(4.32e+05)
Tuzun05	6.60e+01(4.35e+01)	2.98e+02(6.31e+01)	7.44e+02(9.90e+01)	9.81e+01(4.93e+01)	4.53e+05(9.62e+04)	3.09e+04(2.56e+04)	0.00e+00(0.00e+00)	3.81e+05(9.18e+04)
Tuzun06	6.21e+01(3.94e+01)	3.78e+02(7.11e+01)	8.09e+02(7.49e+01)	7.00e+01(3.14e+01)	2.61e+05(5.56e+04)	2.41e+03(4.97e+03)	0.00e+00(0.00e+00)	2.23e+05(4.38e+04)
Tuzun07	6.36e+01(3.03e+01)	1.57e+02(4.81e+01)	3.52e+02(8.77e+01)	7.90e+01(2.99e+01)	1.08e+05(3.65e+04)	1.18e+04(8.75e+03)	6.29e+02(3.45e+03)	7.86e+04(2.34e+04)
Tuzun08	1.79e+02(3.80e+01)	3.09e+02(9.53e+01)	5.02e+02(1.60e+02)	2.09e+02(6.56e+01)	2.32e+04(1.28e+04)	3.29e+03(1.23e+04)	1.85e+00(7.81e+00)	1.28e+04(1.13e+04)
Tuzun09	1.23e+02(3.71e+01)	3.38e+02(6.70e+01)	7.44e+02(1.21e+02)	1.61e+02(6.06e+01)	5.76e+05(9.64e+04)	1.53e+05(4.75e+04)	1.08e+02(5.93e+02)	4.73e+05(9.63e+04)
Tuzun10	7.37e+01(5.21e+01)	4.71e+02(7.76e+01)	9.28e+02(6.98e+01)	1.53e+02(1.19e+02)	4.02e+05(1.47e+05)	6.63e+02(2.29e+03)	0.00e+00(0.00e+00)	2.19e+05(1.15e+05)
Tuzun11	1.33e+02(8.72e+01)	3.47e+02(1.27e+02)	5.60e+02(1.89e+02)	1.63e+02(9.65e+01)	3.01e+05(1.13e+05)	5.42e+04(5.12e+04)	1.66e+04(2.31e+04)	2.63e+05(1.28e+05)
Tuzun12	1.07e+02(7.05e+01)	2.40e+02(8.98e+01)	6.11e+02(5.30e+01)	1.35e+02(9.05e+01)	1.79e+05(5.59e+04)	1.81e+04(1.43e+04)	0.00e+00(0.00e+00)	1.48e+05(4.25e+04)
Tuzun13	1.78e+02(5.64e+01)	8.43e+02(1.04e+02)	2.45e+03(1.10e+02)	3.13e+02(8.98e+01)	1.57e+06(3.61e+05)	2.66e+03(5.38e+03)	0.00e+00(0.00e+00)	8.44e+05(4.00e+05)
Tuzun14	1.35e+02(6.96e+01)	6.00e+02(1.37e+02)	1.67e+03(8.05e+01)	2.18e+02(7.91e+01)	2.90e+06(8.55e+05)	1.05e+05(9.02e+04)	0.00e+00(0.00e+00)	1.64e+06(4.62e+05)
Tuzun15	2.04e+02(4.71e+01)	8.29e+02(1.82e+02)	2.18e+03(1.12e+02)	2.93e+02(7.78e+01)	2.16e+06(4.97e+05)	1.71e+04(4.43e+04)	0.00e+00(0.00e+00)	1.22e+06(4.90e+05)
Tuzun16	1.35e+02(4.33e+01)	7.16e+02(1.18e+02)	1.95e+03(7.16e+01)	2.78e+02(1.33e+02)	3.92e+06(8.22e+05)	1.09e+05(1.43e+05)	0.00e+00(0.00e+00)	2.17e+06(8.67e+05)
Tuzun17	1.44e+02(6.59e+01)	6.27e+02(9.27e+01)	1.79e+03(9.28e+01)	1.94e+02(8.92e+01)	3.03e+05(1.67e+05)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	1.57e+05(1.30e+05)
Tuzun18	1.11e+02(4.12e+01)	6.06e+02(1.03e+02)	1.33e+03(9.95e+01)	1.62e+02(4.98e+01)	3.09e+06(4.50e+05)	3.41e+05(1.70e+05)	0.00e+00(0.00e+00)	2.08e+06(4.27e+05)
Tuzun19	3.26e+02(6.19e+01)	5.31e+02(3.58e+01)	1.23e+03(8.65e+01)	3.80e+02(6.14e+01)	3.03e+05(9.11e+04)	8.40e+03(1.07e+04)	0.00e+00(0.00e+00)	1.86e+05(1.02e+05)
Tuzun20	1.04e+02(3.98e+01)	3.08e+02(7.15e+01)	8.81e+02(5.93e+01)	1.69e+02(3.68e+01)	1.77e+05(4.61e+04)	1.68e+02(4.15e+02)	0.00e+00(0.00e+00)	5.83e+04(2.96e+04)
Tuzun21	1.78e+02(6.49e+01)	7.36e+02(1.07e+02)	1.80e+03(1.20e+02)	2.38e+02(8.20e+01)	1.16e+06(3.73e+05)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	7.98e+05(4.11e+05)
Tuzun22	1.23e+02(4.89e+01)	6.24e+02(1.38e+02)	1.38e+03(9.99e+01)	1.53e+02(6.37e+01)	3.98e+06(5.83e+05)	5.25e+05(2.52e+05)	0.00e+00(0.00e+00)	2.79e+06(5.47e+05)
Tuzun23	3.02e+02(7.40e+01)	6.92e+02(1.12e+02)	1.60e+03(4.65e+02)	3.68e+02(6.95e+01)	4.91e+05(2.69e+05)	1.29e+02(7.08e+02)	0.00e+00(0.00e+00)	2.48e+05(1.44e+05)
Tuzun24	3.51e+01(1.77e+01)	1.31e+02(8.69e+01)	6.25e+02(9.46e+01)	6.38e+01(3.66e+01)	9.00e+04(2.62e+04)	2.78e+03(5.37e+03)	0.00e+00(0.00e+00)	3.57e+04(2.17e+04)
Tuzun25	1.55e+02(6.11e+01)	9.11e+02(1.36e+02)	1.89e+03(3.58e+02)	2.87e+02(1.67e+02)	3.80e+06(7.92e+05)	1.05e+05(1.24e+05)	0.00e+00(0.00e+00)	2.71e+06(1.17e+06)
Tuzun26	1.64e+02(9.00e+01)	6.56e+02(1.17e+02)	1.50e+03(9.34e+01)	2.16e+02(7.24e+01)	2.69e+06(4.42e+05)	7.59e+04(7.82e+04)	0.00e+00(0.00e+00)	2.01e+06(5.67e+05)
Tuzun27	2.03e+02(6.72e+01)	1.03e+03(1.49e+02)	1.90e+03(3.61e+02)	2.85e+02(1.22e+02)	6.29e+05(2.77e+05)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	3.78e+05(2.79e+05)
Tuzun28	1.71e+02(9.11e+01)	6.69e+02(1.20e+02)	1.54e+03(7.58e+01)	2.65e+02(1.23e+02)	4.37e+06(5.22e+05)	6.68e+05(2.29e+05)	0.00e+00(0.00e+00)	3.44e+06(7.45e+05)
Tuzun29	1.23e+02(6.31e+01)	5.80e+02(1.08e+02)	1.33e+03(1.13e+02)	1.76e+02(7.51e+01)	7.03e+05(2.32e+05)	4.63e+04(5.16e+04)	0.00e+00(0.00e+00)	4.83e+05(2.05e+05)
Tuzun30	1.71e+02(8.69e+01)	7.39e+02(1.15e+02)	1.57e+03(9.04e+01)	2.04e+02(6.42e+01)	1.04e+06(3.01e+05)	8.07e+03(1.16e+04)	0.00e+00(0.00e+00)	6.65e+05(2.39e+05)
Tuzun31	5.28e+01(2.60e+01)	1.93e+02(3.68e+01)	6.49e+02(4.55e+01)	7.09e+01(4.02e+01)	1.59e+05(3.72e+04)	2.07e+04(1.13e+04)	0.00e+00(0.00e+00)	1.26e+05(3.39e+04)
Tuzun32	5.20e+01(2.15e+01)	2.06e+02(6.15e+01)	6.35e+02(5.09e+01)	1.12e+02(1.03e+02)	5.74e+04(2.34e+04)	3.29e+02(1.04e+03)	0.00e+00(0.00e+00)	2.75e+04(1.66e+04)
Tuzun33	1.45e+02(9.13e+01)	8.25e+02(1.27e+02)	1.83e+03(9.67e+01)	1.50e+02(9.15e+01)	1.28e+06(3.71e+05)	3.13e+04(5.13e+04)	0.00e+00(0.00e+00)	1.14e+06(3.57e+05)
Tuzun34	1.30e+02(4.79e+01)	3.29e+02(7.52e+01)	7.03e+02(7.68e+01)	1.61e+02(7.17e+01)	2.39e+06(2.36e+05)	9.31e+05(1.55e+05)	2.41e+03(9.50e+03)	2.01e+06(2.50e+05)
Tuzun35	3.26e+02(9.66e+01)	8.18e+02(1.26e+02)	9.41e+02(2.07e+02)	3.72e+02(1.26e+02)	3.44e+02(1.62e+03)	0.00e+00(0.00e+00)	0.00e+00(0.00e+00)	5.76e-01(2.23e+00)
Tuzun36	7.42e+01(2.38e+01)	1.83e+02(6.77e+01)	6.11e+02(7.63e+01)	1.18e+02(5.97e+01)	1.16e+05(3.02e+04)	1.16e+04(1.05e+04)	0.00e+00(0.00e+00)	7.61e+04(3.33e+04)

D. An Example of the Confliction Between the Objectives

We investigate the confliction of the objectives in our MOLRP model as a supplement to *Section V-D*. A simplified example is shown in Fig. 2.

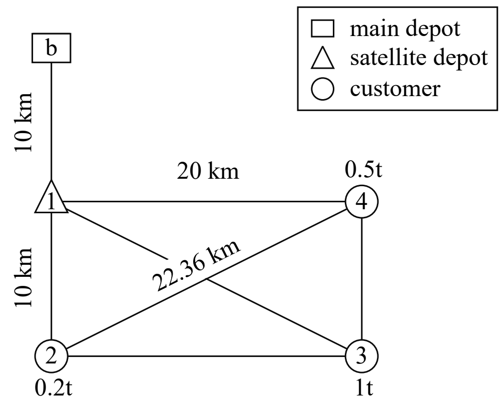

Fig. 2. An example of the MOLRP for biomass waste collection.

There is only one satellite depot and no capacity constraint on the satellite depot or the vehicle. According to the given distances on all arcs and the amount of biomass waste on customer nodes, we find three non-dominant solutions represented by the customer visiting sequences “1-2-3-4-1”, “1-4-3-2-1” and “1-3-4-2-1”, with the objective function values $(565.00, 0.74, 22.03)^{\mathrm{T}}$, $(565.00, 0.72, 22.09)^{\mathrm{T}}$ and $(569.72, 0.70, 23.75)^{\mathrm{T}}$, respectively. Compared with the conventional minimum-distance models, which has two equal optimum solutions “1-2-3-4-1” and “1-4-3-2-1”, our model provides more evaluation aspects to illustrate the difference between these two solutions, and offers an alternative solution. Among the three non-dominant solutions, we can learn the different routing strategies. To minimize F_1, the vehicle should go along the shortest route for a lower distance-based cost. On the shortest route, if the vehicle visits small-stock customers first, the vehicle will carry a relative light load on its trip, so that emission can be reduced. However, if the decision maker leans towards reducing pollution, it will require the vehicle to head to the large-stock customers in advance, and even abandon the shortest route. To sum up, the strategy of customer visiting sequence is an important factor to tilt the trade-off among the objectives, and a relative short route is the basic requirement for all objectives.

E. Investigation on the Population Division Method of MPGA

To further investigate into our improvement on GA, we compare FR-NSGA-II with MPGA on an example instance to show their performances on each iteration. In Fig. 3, we plot the number of location decisions obtained by the current population and the IGD value in each iteration. It can be seen that MPGA has a sharp drop on the number of current location decisions in the first 20 iterations, while FR-NSGA-II descends slower, fluctuating in the following iterations, and finally falls below the line of MPGA. It stems from the stochastic combination of solutions with different structures, that it takes a broad search of the decision space for location, but much of them can be infeasible or invaluable. This is also an evidence for our multi-population strategy to be able to obtain a good location decisions quickly, and continue to optimize the routing decision as IGD decreases with the stable location decisions.

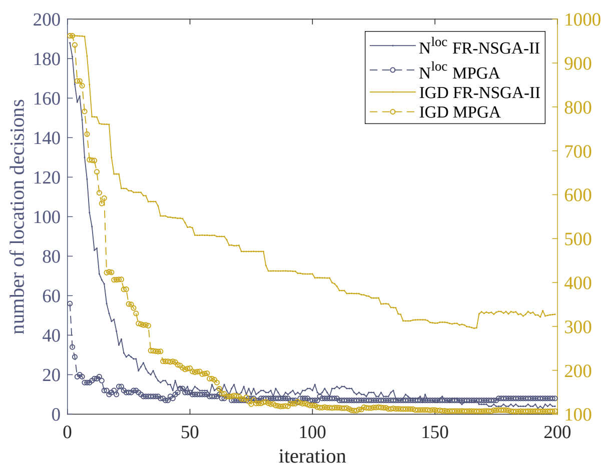

Fig. 3. Comparison between MPGA and FR-NSGA-II during iterations.

F. Investigation on the Pheromone Segregation Strategy of SPACO

Turning now to the experimental evidence on our pheromone segregation strategy of SPACO, we illustrate the solutions obtained by ACO-based algorithms in Fig. 4. The example solutions are selected from the non-dominant set in the last iteration, by identifying the nearest one to the ideal solution. The black solid lines are the vehicle routes passing through the customers and satellite depots. The black dash lines indicate the routes where vehicles route between the satellite depots and the main depot. We use colored lines to represent the pheromones on the network. The thicker the line is, the greater the amount of pheromone is on the route. Therefore, for MCACO, there is one general pheromone for all different ants. MPACO leaves objective-independent pheromones as distinguished by different colors. SPACO adopts the strategy that routing pheromones related to each satellite depot should be segregated, and they are also indicated by distinctive colors.

From the comparison between Fig. 4(a)-(c), it shows that the pheromones fuse into a connected network for MCACO and MPACO. Then, the ants can be misled by (i) the pheromones from other satellite depots, and (ii) the pheromones from other non-dominant solutions. The drawback is not obvious on the small-scale evenly-distributed instance, whereas it can cause undesired results in a more complex instance (Fig. 4(d)-(f)). It can be seen that the pheromone traces of our SPACO determine a clear partition of the customers. Though different pheromones can flow to a junction, the ants will not trespass the unidentified areas.

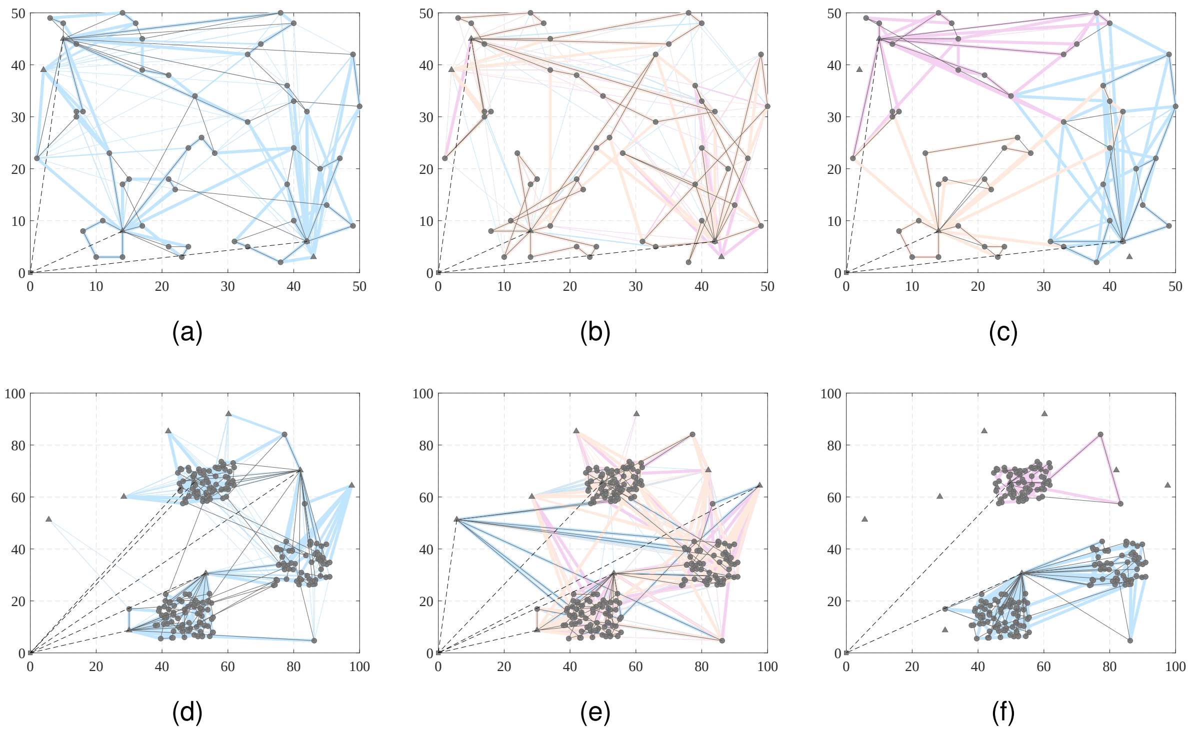

Fig. 4. A comparison on the solutions obtained by ACO-based algorithms. They are selected from the non-dominant set with the minimum distances to the ideal solutions[1] of the example instances. (a) MCACO on Prodhon05. (b) MPACO on Prodhon05. (c) SPACO on Prodhon05. (d) MCACO on Tuzun19. (e) MPACO on Tuzun19. (f) SPACO on Tuzun19.

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[1] The “ideal solution” refers to a solution which is constructed by the optimal values of each of the objective functions [1].

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