The supplementary file of the paper "Multi-agent Coalition Formation by An Efficient Genetic Algorithm with Heuristic Initialization and Repair Strategy"

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Abstract

This PDF is the supplementary file of the paper "Multi-agent Coalition Formation by An Efficient Genetic Algorithm with Heuristic Initialization and Repair Strategy". The detailed algorithm flow, experimental data, parameter settings, etc. are available in this PDF. This PDF is publicly available at GitHub (https://github.com/luzaijiaoxia/SWEVO_supplementary_file).

1. GAHIR for STSCF/MTSCF

1.1. Random initialization

The random initialization method means that each agent joins the coalition with the probability of 0.5. The algorithm flow is described in Algorithm 1.

1.2. Decremental heuristic initialization

Decremental heuristic initialization firstly generates N_p random solutions by the random initialization in Section 1.1. Then, for N out of N_p solutions, the deletion operation will be performed until all superfluous agents have been deleted (N is equal to rounded $\frac{N_p}{2}$). The algorithm flow is shown in Algorithm 2.

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Algorithm 1 Random initialization for STSCF/MTSCF

for $s = 1$ to N_p **do**
  for $i = 1$ to n **do**
    if $rand < 0.5$ $(rand \in (0,1))$ **then**
      The agent a_i joins the coalition C.
    end if
  end for
  Add the coalition into the initial population P_{ini}.
end for

Algorithm 2 Decremental heuristic initialization for STSCF/MTSCF

for $s = 1$ to N_p **do**
  Add the coalition into the initial population P_{ini} generated by the random initialization in Algorithm 1.
end for
for $s = 1$ to N **do**
  repeat
    Obtain a list S_A in which deleting any agent does not break constraints in the current coalition C.
    Randomly delete an agent a_i $(a_i \in S_A)$.
  until there are not superfluous agents in the coalition C.
end for

1.3. Hybrid repair strategy

Similar to the incremental heuristic initialization, the hybrid repair strategy (HY) will also be designed according to specific problems. The specific flow of the hybrid repair strategy is shown in Algorithm 3.

Algorithm 3 Hybrid repair strategy for STSCF/MTSCF

for $s = 1$ to N_p **do**
  if the sth coalition C is an infeasible solution **then**
    Compute the remaining requirement on the jth ability of the task $R_t^j = \min\{q_t^j - q_c^j, 0\}$ $(j \in \{1, 2, \ldots, r\})$, the sum of the jth ability of every unassigned agent $R_B^j = \sum\limits_{a_i \in R_A} b_i^j$ $(j \in \{1, 2, \ldots, r\})$, the set of the unassigned agents R_A $(R_A \cup C = A$ and $R_A \cap C = \emptyset)$.
    repeat
      if $rand < \gamma$ $(rand \in (0, 1))$ **then**
        Randomly select an agent a_i $(a_i \in R_A)$ to join the sth coalition C.
      else
        Compute the value $f_i = (\sum_{j=1}^{r} \frac{R_t^j}{R_B^j} \times b_i^j)/d_i$ $(a_i \in R_A)$.
        Select the agent a_i $(a_i \in R_A)$ which has the maximum value of f_i to join the coalition.
      end if
      Update R_A, R_t^j and R_B^j $(j \in \{1, 2, \ldots, r\})$.
    until the coalition C becomes a feasible solution.
  end if
end for

2. GAHIR for MTMCF

2.1. Random initialization

Each solution in the initial population is randomly generated as shown in Algorithm 4. In each solution (coalition scheme), each agent is selected to join a coalition with the probability of 0.5. If an agent is selected to join a coalition, it can randomly join any task coalition.

2.2. Decremental heuristic initialization

The decremental heuristic initialization firstly generates random solutions. Then, superfluous agents will be deleted from each task coalition if the dele-

Algorithm 4 Random initialization for MTMCF

for $s = 1$ to N_p **do**
    for $i = 1$ to n **do**
        if $rand < 0.5$ ($rand \in (0, 1)$) **then**
            The agent a_i joins any coalition C_k ($k \in \{1, 2, \ldots, m\}$).
        end if
    end for
    Add all coalitions C_k ($\forall\ k \in \{1, 2, \ldots, m\}$) into the initial population P_{ini}.
end for

Algorithm 5 Decremental heuristic initialization for MTMCF

for $s = 1$ to N_p **do**
    Add the coalition into the initial population P_{ini} generated by the random initialization in Algorithm 4.
end for
for $s = 1$ to N **do**
    for $k = 1$ to m **do**
        repeat
            Obtain a list S_A in which deleting any agent does not violate constraints in the current coalition C_k.
            Randomly delete an agent a_i ($a_i \in S_A$).
        until there are not superfluous agents in the coalition C_k.
    end for
end for

tion does not violate the constraints. The detail of the decremental heuristic initialization is shown in Algorithm 5 where N is equal to rounded $\frac{N_p}{3}$.

2.3. Hybrid repair strategy

The hybrid repair strategy (HY) repairs solutions by adding unassigned agents to the coalitions which do not satisfy the ability requirements of the cor-

Algorithm 6 Hybrid repair strategy for MTMCF

for $s = 1$ to N_p **do**

  Initialize the set of the unassigned agents R_A, the remaining requirement on the jth ability of the kth task $R_{t_k}^j = \min\{p_{t_k}^j - p_{c_k}^j, 0\}$ $(k \in \{1, 2, \ldots, m\},\ j \in \{1, 2, \ldots, r\})$, the sum of the jth ability of every unassigned agent $R_B^j = \sum_{a_i \in R_A} b_i^j$ $(j \in \{1, 2, \ldots, r\})$.

  if there exists a coalition C_k of the sth individual is infeasible **then**

    repeat

      if $rand < \gamma$ $(rand \in (0, 1))$ **then**

        Randomly select an agent a_i $(a_i \in R_A)$ to join any coalition C_k $(k \in \{1, 2, \ldots, m\})$ which does not satisfy the task constraints.

      else

        Compute the value $s_k^j = \frac{R_{t_k}^j}{R_B^j}$, $f_k^i = \sum_{j=1}^{r} (\frac{s_k^j}{\sum_{j=1}^{r} s_k^j} \times b_i^j)/d_i$ $(a_i \in R_A)$.

        Select the agent a_i to join the coalition C_k which has the maximum value of f_k^i.

      end if

      Update $R_A, R_{t_k}^j$ and R_B^j $(k \in \{1, 2, \ldots, m\},\ j \in \{1, 2, \ldots, r\})$.

    until all coalitions C_k $(\forall\ k \in \{1, 2, \ldots, m\})$ satisfy the requirements of the corresponding tasks or R_A is an empty set.

  end if

end for

responding tasks. The repair method is based on the heuristic rules in the incremental heuristic initialization. The detail of the repair strategy is shown in Algorithm 6.

3. Experiments and Results

All experiments were carried out in MATLAB R2016a environment on a PC with Intel(R) Core(TM) i5-7500 @3.40GHz and 16GB RAM.

3.1. Parameter settings of compared methods

In the paper, the random sampling [1], the binary monarch butterfly optimization method [2] and the improved genetic algorithm-simulated annealing [3] are taken as competitors in the experiment. Some parameters of the compared methods were appropriately tuned and the remaining parameters were set to the setup of the presenters. How parameters of compared methods were tuned is shown as follows.

Table 1: Parameter settings of compared methods

Algorithm	Parameter	Description	Value
IGA-SA	N_p	population size	100
	P_c	crossover rate in the GA	0.8
	P_m	mutation rate in the GA	0.2
	K	the size of tournament selection in the GA	20
	L	maximum iterations in the SA	250
	T	maximum temperature in the SA	2500
	α	temperature change in the SA	0.9
BMBO	N_p	population size	$3n$
	p	migration ratio	5/12
	$peri$	migration period	1.2
	S_{max}	the max walk step of Levy flights	1.0
	$Maxgen$	maximum number of iterations	50
	BAR	butterfly adjusting rate	5/12
	RG	generation interval between recombination	50
/	NFE_{max}	maximum number of function evaluations	$2000n$

- Random Sampling (RS)[1]

  All parameters are set as those of the presenters. The probability that each agent is assigned is 0.5.

- Binary Monarch Butterfly Optimization (BMBO) Method [2]

  The parameter settings of BMBO are shown in Table 1. The population size N_p is set to $3n$ in this paper (the setup of N_p of the presenters is 50). The remaining parameters of BMBO are set as those of the presenters. The results of different N_p of BMBO are shown in Table 2. n represents the number of agents in each instance. Comprehensively, the larger population size is more beneficial to solve the problem. In Table 2, the $Score$ represents the score of each algorithm for solving different instances, and their scores are evaluated based on the results of the statistical analysis and Wilcoxons rank-sum tests with the significance level of 0.05. One algorithm gets a point as long as the Wilcoxons rank-sum test has demonstrated its performance is obviously better than another with regard to the mean of objective values in 20 runs for a certain instance.

Table 2: Experimental results of BMBO

No.	Objective value	
	$N_p = 50$	$N_p = 3n$
1	253.60 ± 2.68	253.00 ± 0.00
2	1320.35 ± 13.34	1314.60 ± 8.31
3	708.80 ± 26.63	**686.05 ±17.45**
4	3929.90 ± 27.61	**3912.15 ±0.37**
5	9157.15 ±72.92	**9085.80 ±77.34**
6	8572.70 ±207.68	**7754.80 ±212.61**
7	10320.10 ±241.92	**9264.65 ±261.39**
8	17774.25 ±194.92	**17003.25 ±394.93**
9	17952.65 ±325.58	**15730.15 ±359.33**
10	10701.60 ±496.26	**7709.60 ±338.13**
11	28904.30 ±358.77	**27413.05 ±596.25**
12	38716.35 ± 324.75	**38192.50 ±235.74**
Score	0	**10**

- Improved Genetic Algorithm-simulated Annealing (IGA-SA) [3]

  All parameters are set as those of the presenters. The parameter settings of IGA-SA are shown in Table 1.

3.2. Results and analysis about STSCF

3.2.1. Comparison about different combinations of initialization methods and constraint handling strategies

In this comparison experiment, the effect of different combinations of initialization methods and constraint handling strategies will be compared. The detailed results of the statistical analysis are shown in Table 3.

3.2.2. Comparison between GAHIR, IGA-SA, BMBO and RS

The convergence curves of GAHIR, IGA-SA, BMBO and RS in all instances are shown in Figure 1. The horizontal axis and the vertical axis represent the

Table 3: Results of the comparison between the variants of GAHIR with different combinations of initialization methods and constraint handling strategies for STSCF

No.	GAHIR-RI-PF	GAHIR-RI-RR	GAHIR-RI-HY	GAHIR-RI-HR
1	**253.00 ± 0.00**	**253.00 ± 0.00**	**253.00 ± 0.00**	**253.00 ± 0.00**
2	**1310.00 ± 0.00**	**1310.00 ± 0.00**	**1310.00 ± 0.00**	**1310.00 ± 0.00**
3	**669.35 ± 6.04**	**668.00 ± 0.00**	**668.00 ± 0.00**	**668.00 ± 0.00**
4	**3912.00 ± 0.00**	**3912.00 ± 0.00**	**3912.00 ± 0.00**	**3912.00 ± 0.00**
5	**8889.00 ± 0.00**	**8889.00 ± 0.00**	**8889.00 ± 0.00**	**8889.00 ± 0.00**
6	7148.80 ± 4.70	**7146.00 ± 0.00**	**7146.00 ± 0.00**	**7146.00 ± 0.00**
7	8306.70 ± 4.50	8302.35 ±1.93	8302.20 ± 1.96	8304.30 ± 1.49
8	15348.25 ± 8.49	15340.40 ± 6.17	15340.75 ± 4.89	15343.85 ± 3.76
9	13274.40 ± 7.74	13265.55 ± 3.00	**13263.00 ± 0.00**	**13263.00 ± 0.00**
10	**5875.25 ± 3.39**	**5873.90 ± 2.17**	5880.35 ± 4.20	5883.20 ± 4.01
11	23753.90 ± 7.76	23752.70 ± 6.41	23753.55 ± 4.97	23757.10 ± 1.41
12	33839.85 ± 6.19	33836.70 ± 4.57	33838.05 ± 4.73	33845.30 ± 3.26
Score	**22**	**50**	**46**	**28**

No.	GAHIR-II-PF	GAHIR-II-RR	GAHIR-II-HY	GAHIR-II-HR
1	**253.00 ± 0.00**	**253.00 ± 0.00**	**253.00 ± 0.00**	**253.00 ± 0.00**
2	**1310.00 ± 0.00**	**1310.00 ± 0.00**	**1310.00 ± 0.00**	**1310.00 ± 0.00**
3	**668.00 ± 0.00**	**668.00 ± 0.00**	**668.00 ± 0.00**	**668.00 ± 0.00**
4	**3912.00 ± 0.00**	**3912.00 ± 0.00**	**3912.00 ± 0.00**	**3912.00 ± 0.00**
5	**8889.00 ± 0.00**	**8889.00 ± 0.00**	**8889.00 ± 0.00**	**8889.00 ± 0.00**
6	**7146.00 ± 0.00**	**7146.00 ± 0.00**	**7146.00 ± 0.00**	**7146.00 ± 0.00**
7	**8300.15 ± 0.67**	**8300.00 ± 0.00**	8304.40 ± 1.82	8304.65 ± 1.84
8	15338.65 ± 2.56	**15335.90 ± 2.17**	15344.00 ± 4.27	15346.60 ± 2.84
9	13267.75 ± 3.99	13263.85 ±1.57	**13263.00 ± 0.00**	13263.75 ± 1.55
10	**5874.15 ± 3.03**	**5873.35 ± 2.23**	5883.80 ± 3.30	5883.45 ± 3.15
11	23739.50 ± 5.41	**23736.00 ± 0.00**	23755.50 ± 3.07	23757.85 ± 0.67
12	**33834.00 ± 0.00**	**33834.00 ± 0.00**	**33834.00 ± 0.00**	**33834.00 ± 0.00**
Score	**67**	**77**	**36**	**30**

No.	GAHIR-DI-PF	GAHIR-DI-RR	GAHIR-DI-HY	GAHIR-DI-HR
1	**253.00 ± 0.00**	**253.00 ± 0.00**	**253.00 ± 0.00**	**253.00 ± 0.00**
2	**1310.00 ± 0.00**	**1310.00 ± 0.00**	**1310.00 ± 0.00**	**1310.00 ± 0.00**
3	**668.00 ± 0.00**	**668.00 ± 0.00**	**668.00 ± 0.00**	**668.00 ± 0.00**
4	**3912.00 ± 0.00**	**3912.00 ± 0.00**	**3912.00 ± 0.00**	**3912.00 ± 0.00**
5	**8889.00 ± 0.00**	**8889.00 ± 0.00**	**8889.00 ± 0.00**	**8889.00 ± 0.00**
6	7148.10 ± 3.75	**7146.00 ± 0.00**	**7146.00 ± 0.00**	**7146.00 ± 0.00**
7	8307.90 ± 5.17	8301.70 ±2.05	8302.70 ± 2.00	8304.90 ± 1.02
8	15348.65 ± 8.98	**15339.40 ± 6.26**	15341.20 ± 3.61	15344.35 ± 4.04
9	13275.45 ± 7.09	13265.75 ±3.32	**13263.00 ± 0.00**	**13263.40 ± 1.23**
10	5876.70 ± 3.51	**5874.10 ± 2.34**	5878.75 ±4.80	5881.85 ± 4.68
11	23751.80 ± 7.69	23750.65 ± 9.08	23753.80 ± 2.24	23757.25 ± 1.33
12	33844.55 ± 7.04	33838.10 ± 5.30	33836.40 ± 4.38	33845.80 ± 0.89
Score	**20**	**47**	**51**	**22**

No.	GAHIR-HI-PF	GAHIR-HI-RR	GAHIR-HI-HY	GAHIR-HI-HR
1	**253.00 ± 0.00**	**253.00 ± 0.00**	**253.00 ± 0.00**	**253.00 ± 0.00**
2	**1310.00 ± 0.00**	**1310.00 ± 0.00**	**1310.00 ± 0.00**	**1310.00 ± 0.00**
3	**668.00 ± 0.00**	**668.00 ± 0.00**	**668.00 ± 0.00**	**668.00 ± 0.00**
4	**3912.00 ± 0.00**	**3912.00 ± 0.00**	**3912.00 ± 0.00**	**3912.00 ± 0.00**
5	**8889.00 ± 0.00**	**8889.00 ± 0.00**	**8889.00 ± 0.00**	**8889.00 ± 0.00**
6	7183.40 ± 21.13	**7146.00 ± 0.00**	**7146.00 ± 0.00**	**7146.00 ± 0.00**
7	8320.00 ± 0.00	8305.60 ± 1.35	8305.10 ± 1.02	8305.25 ± 1.48
8	15402.10 ± 9.16	15339.00 ± 0.00	**15336.20 ± 3.69**	15337.80 ± 4.29
9	13382.25 ± 35.68	13283.90 ± 9.16	13266.55 ± 3.22	13266.95 ± 2.98
10	5878.00 ± 0.00	5878.00 ± 0.00	5877.35 ± 2.06	5877.60 ± 1.79
11	23822.30 ± 15.28	23768.30 ± 3.37	23756.80 ± 4.14	23755.90 ± 2.20
12	33920.70 ± 13.88	33857.80 ± 0.89	33853.75 ± 3.73	33845.35 ± 8.15
Score	**6**	**23**	**32**	**31**

number of objective function evaluations and the mean value of the results of each algorithm in 20 runs, respectively.

3.3. Results and analysis about MTMCF

3.3.1. Comparison about different combinations of initialization methods and constraint handling strategies

In this comparison experiment, the effect of different combinations of initialization methods and constraint handling strategies will be tested. The results of statistical analysis in all instances are shown in Table 4.

3.3.2. Comparison between GAHIR and RS

For verifying the performance of GAHIR, GAHIR will be compared with RS. In this experiment, GAHIR will adopt the decremental heuristic initialization (DI) and the heuristic repair strategy (HR). The box plots of GAHIR and RS are shown in Figure 2. The convergence curves of GAHIR and RS in all instances are shown in Figure 3. The horizontal axis and the vertical axis represent the number of objective function evaluations and the mean value of results of each algorithm in 20 runs, respectively.

3.3.3. Extension experiment of GAHIR

We additionally conducted the experiment of CPLEX and GAHIR for larger-scale instances, with the purpose of further studying the performance of GAHIR in larger-scale instances. The experimental results are shown in Table 5 where n.a. means that CPLEX cannot obtain global optima within two hours or the computer is out of memory. From the results of the further experiment, we conclude that CPLEX cannot obtain global optima within acceptable time (2 hours) in many larger-scale instances, and GAHIR can provide feasible solutions of good quality for the same instance. Furthermore, for the instances whose optima can be obtained by CPLEX, it can be seen that the optimality gap between GAHIR and the optima is small, which indicates that GAHIR has good performance in solving the problem.

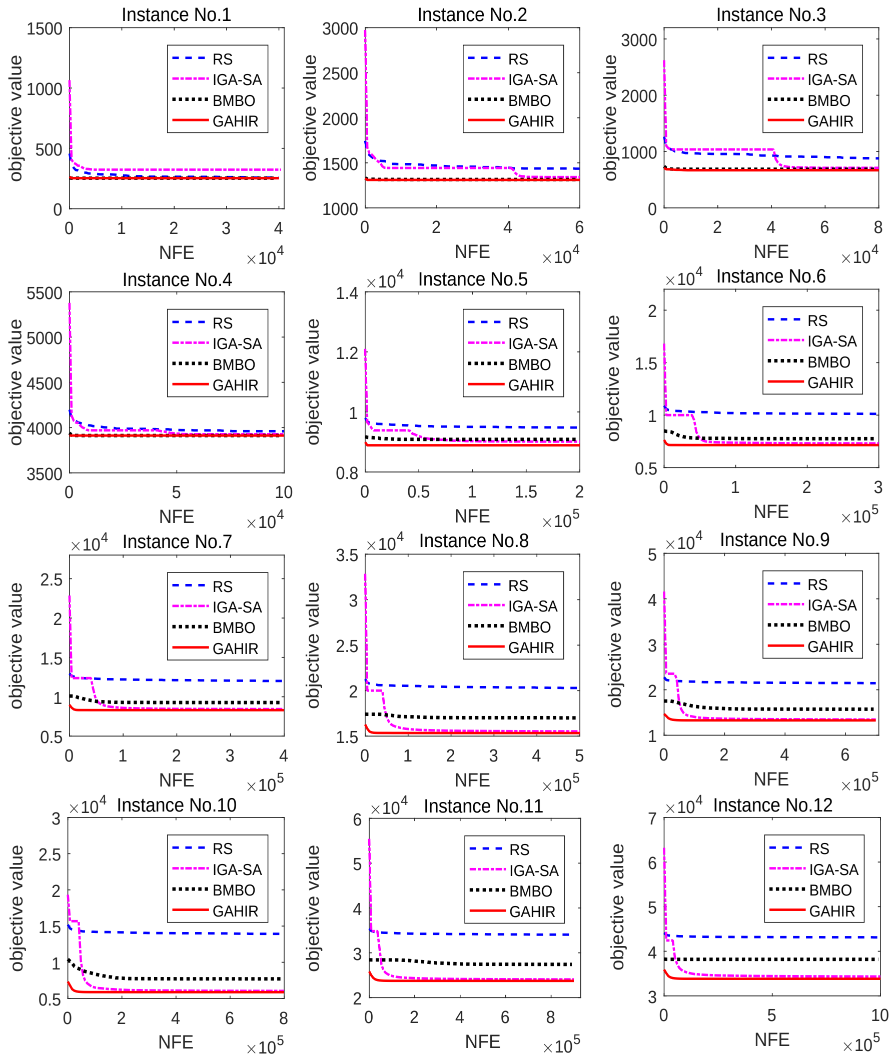

Figure 1: Convergence curves of GAHIR, IGA-SA, BMBO and RS for STSCF

Table 4: Results of the comparison between the variants of GAHIR with different combinations of initialization methods and constraint handling strategies for MTMCF

No.	GAHIR-RI-PF	GAHIR-RI-RR	GAHIR-RI-HY	GAHIR-RI-HR
1	**493.00 ± 0.00**	**493.00 ± 0.00**	**493.00 ± 0.00**	**493.00 ± 0.00**
2	841.90 ± 15.98	**834.30 ± 8.06**	**832.10 ± 4.92**	**831.00 ± 0.00**
3	807.24 ± 17.86	**794.00 ± 0.00**	**794.00 ± 0.00**	**794.00 ± 0.00**
4	1451.35 ± 18.64	**1440.30 ± 9.91**	**1443.00 ± 11.21**	1460.20 ± 7.80
5	1522.30 ± 93.82	1345.90 ± 34.19	1309.25 ± 20.92	**1286.00 ± 14.65**
6	2660.23 ± 222.36	**2083.40 ± 19.50**	**2076.00 ± 10.08**	**2078.60 ± 11.63**
7	2143.45 ± 50.01	2061.05 ± 30.34	2030.80 ± 24.61	**2016.50 ± 13.27**
8	3432.45 ± 91.81	3210.95 ± 55.77	3144.35 ± 35.85	**3095.85 ± 39.34**
9	4634.97 ± 273.58	2982.85 ± 87.33	**2892.55 ± 59.38**	**2883.45 ± 37.59**
10	3205.55 ± 96.64	3030.45 ± 56.51	2952.55 ± 46.02	**2906.70 ± 29.38**
11	3755.95 ± 113.31	3326.80 ± 89.75	3184.90 ± 66.31	**3126.10 ± 49.30**
12	8795.46 ± 769.01	5703.55 ± 113.72	**5580.55 ± 137.15**	**5532.00 ± 99.82**
13	4427.40 ± 81.93	4239.90 ± 66.88	**4127.90 ± 40.35**	**4106.20 ± 42.95**
14	4947.80 ± 222.39	4270.00 ± 112.55	4030.90 ± 68.32	**3981.00 ± 90.88**
15	12701.29 ± 1051.79	7773.20 ± 223.35	**7525.05 ± 113.95**	**7435.20 ± 122.17**
Score	**9**	**62**	**103**	**109**

No.	GAHIR-II-PF	GAHIR-II-RR	GAHIR-II-HY	GAHIR-II-HR
1	**493.00 ± 0.00**	**493.00 ± 0.00**	**493.00 ± 0.00**	**493.00 ± 0.00**
2	844.65 ± 16.90	**834.00 ± 9.59**	**831.00 ± 0.00**	**831.00 ± 0.00**
3	**795.00 ± 4.45**	**794.00 ± 0.00**	**794.00 ± 0.00**	**794.00 ± 0.00**
4	1464.40 ± 20.43	1460.70 ± 12.91	1449.00 ± 13.44	1456.55 ± 10.34
5	1503.05 ± 79.79	1353.75 ± 50.62	**1291.35 ± 20.92**	**1291.25 ± 17.91**
6	2504.16 ± 218.45	2086.75 ± 18.40	**2076.00 ± 10.02**	**2079.50 ± 13.38**
7	2128.60 ± 36.76	2053.00 ± 29.62	**2013.95 ± 23.62**	**2018.90 ± 12.03**
8	3340.45 ± 86.97	3190.00 ± 50.62	3148.30 ± 37.54	**3120.35 ± 41.16**
9	4037.10 ± 359.21	3048.05 ± 83.87	2928.45 ± 77.60	**2892.25 ± 66.23**
10	3181.90 ± 84.51	3014.40 ± 52.81	2944.05 ± 38.67	2906.85 ± 14.67
11	3634.00 ± 139.81	3305.85 ± 101.97	**3159.80 ± 70.58**	**3125.30 ± 66.67**
12	8492.24 ± 760.16	5675.40 ± 162.85	5625.35 ± 151.98	**5549.05 ± 126.50**
13	4380.00 ± 52.71	4242.00 ± 51.33	**4131.30 ± 52.07**	**4124.80 ± 24.52**
14	4687.25 ± 154.49	4183.55 ± 77.97	**4021.40 ± 89.93**	**3992.55 ± 59.85**
15	11511.73 ± 653.48	7684.50 ± 176.87	**7493.15 ± 128.67**	**7497.60 ± 121.56**
Score	**18**	**52**	**98**	**103**

No.	GAHIR-DI-PF	GAHIR-DI-RR	GAHIR-DI-HY	GAHIR-DI-HR
1	**493.00 ± 0.00**	**493.00 ± 0.00**	**493.00 ± 0.00**	**493.00 ± 0.00**
2	840.00 ± 14.80	**833.20 ± 6.77**	**832.90 ± 8.50**	**831.00 ± 0.00**
3	800.25 ± 15.18	**794.00 ± 0.00**	**794.00 ± 0.00**	**794.00 ± 0.00**
4	1453.15 ± 14.63	**1440.00 ± 11.89**	**1441.60 ± 12.44**	1460.75 ± 8.85
5	1538.05 ± 69.04	1375.90 ± 56.21	1302.70 ± 24.57	**1291.35 ± 20.92**
6	2684.75 ± 244.10	2090.00 ± 20.35	**2077.30 ± 10.67**	**2075.05 ± 9.75**
7	2156.65 ± 45.34	2065.80 ± 30.98	**2015.35 ± 31.88**	**2014.50 ± 20.42**
8	3473.30 ± 104.95	3189.70 ± 47.69	3153.30 ± 49.62	**3108.90 ± 38.62**
9	4509.95 ± 421.56	3003.55 ± 110.05	2926.35 ± 48.81	**2902.60 ± 53.86**
10	3197.10 ± 72.41	3022.45 ± 41.12	2928.20 ± 33.69	**2896.30 ± 13.41**
11	3758.95 ± 162.99	3304.50 ± 77.67	**3157.85 ± 61.02**	**3117.00 ± 64.41**
12	9285.69 ± 757.95	5713.60 ± 221.14	**5517.75 ± 94.60**	**5562.25 ± 108.96**
13	4478.05 ± 91.40	4225.30 ± 46.16	**4134.25 ± 34.69**	**4118.25 ± 44.28**
14	4963.60 ± 163.54	4280.65 ± 99.86	4051.85 ± 89.28	**4004.95 ± 73.81**
15	12852.69 ± 1209.37	7857.50 ± 187.55	**7494.10 ± 143.04**	**7459.10 ± 118.47**
Score	**7**	**62**	**100**	**110**

No.	GAHIR-HI-PF	GAHIR-HI-RR	GAHIR-HI-HY	GAHIR-HI-HR
1	**493.00 ± 0.00**	**493.00 ± 0.00**	**493.00 ± 0.00**	**493.00 ± 0.00**
2	844.70 ± 13.55	**831.00 ± 0.00**	**831.00 ± 0.00**	**831.00 ± 0.00**
3	796.07 ± 4.70	**794.00 ± 0.00**	**794.00 ± 0.00**	**794.00 ± 0.00**
4	1462.30 ± 5.98	1459.60 ± 9.34	1450.30 ± 14.61	1461.15 ± 6.96
5	1488.55 ± 68.27	1372.50 ± 66.47	1301.75 ± 27.28	**1298.55 ± 32.35**
6	2696.96 ± 157.90	2086.50 ± 12.92	**2077.25 ± 10.59**	**2077.45 ± 13.13**
7	2092.75 ± 32.15	2044.85 ± 27.45	**2016.90 ± 14.97**	**2011.70 ± 14.07**
8	3314.10 ± 65.87	3173.55 ± 59.29	3147.05 ± 49.24	**3106.60 ± 31.82**
9	3888.95 ± 139.38	3055.10 ± 99.01	**2899.10 ± 52.26**	**2896.90 ± 50.46**
10	3202.40 ± 90.31	3020.90 ± 48.30	2924.65 ± 28.94	2913.50 ± 28.27
11	3693.40 ± 100.89	3283.10 ± 59.56	3168.25 ± 68.31	**3119.90 ± 52.36**
12	7952.89 ± 270.85	5657.10 ± 107.39	**5550.85 ± 103.74**	**5522.60 ± 82.94**
13	4389.40 ± 59.14	4216.70 ± 36.91	**4133.40 ± 41.97**	**4125.95 ± 41.19**
14	4551.35 ± 77.21	4184.90 ± 86.06	4068.10 ± 96.70	**3980.10 ± 70.77**
15	11374.71 ± 375.11	7745.60 ± 152.58	**7538.85 ± 130.87**	**7449.95 ± 136.04**
Score	**19**	**54**	**101**	**110**

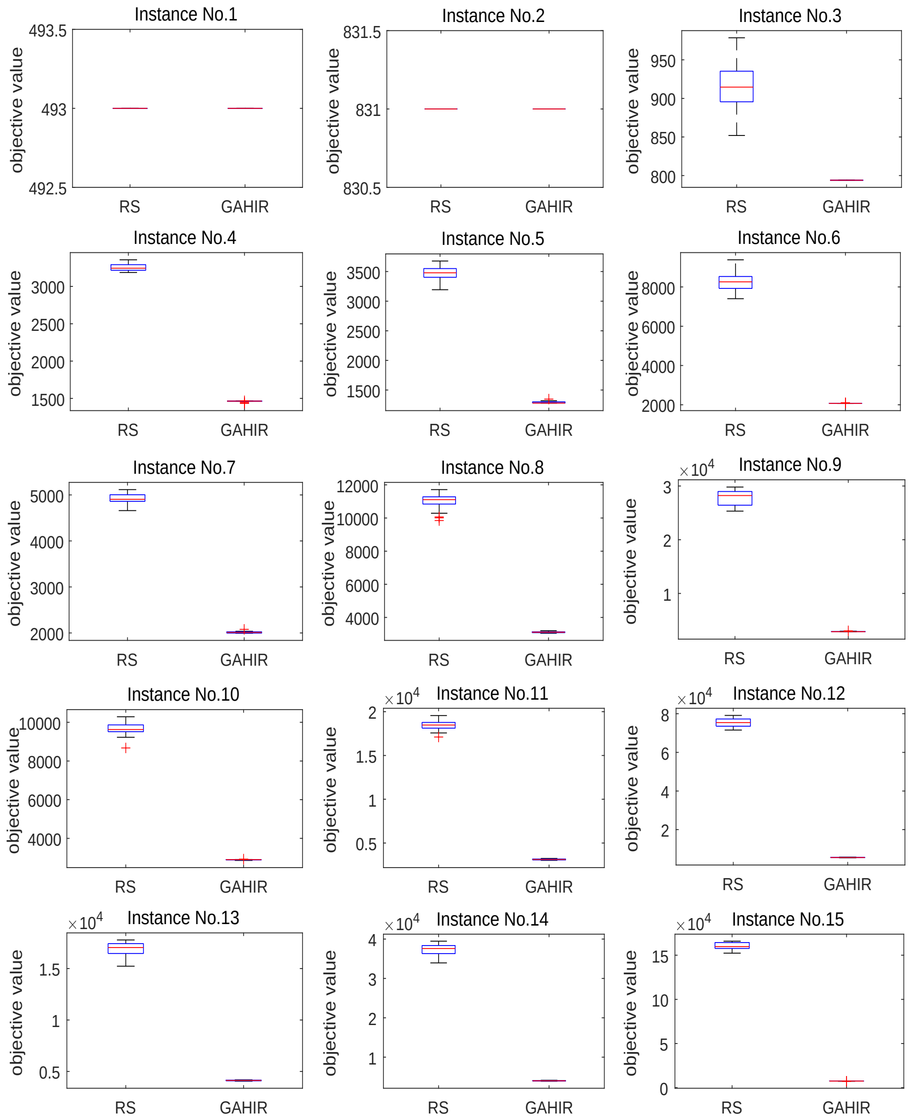

Figure 2: Box plots of GAHIR and RS for MTMCF

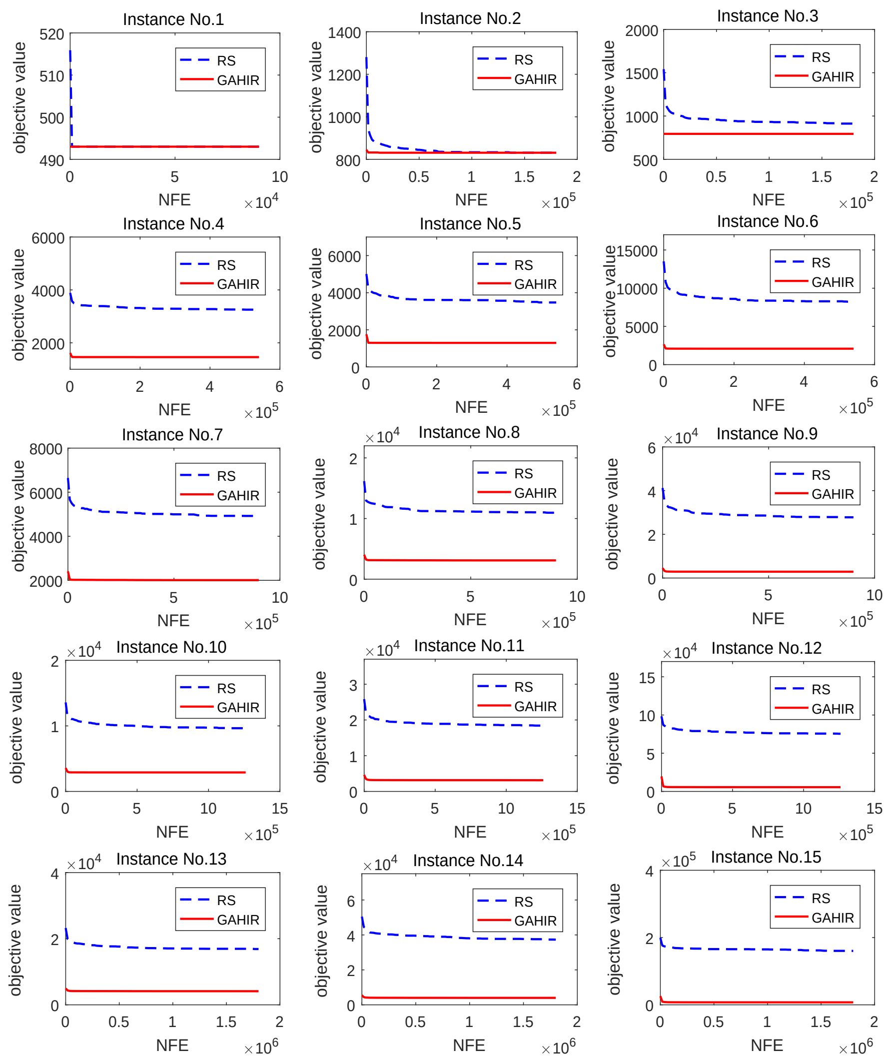

Figure 3: Convergence curves of GAHIR and RS for MTMCF

Table 5: The objective values of the GAHIR in solving larger-scale instances for MTMCF

No.	n	m	Objective value	
			GAHIR	f^*(CPLEX)
1	80	8	3934.00±27.85	**3792.00**
2		10	**4390.70±49.55**	n.a
3		16	**4040.65±67.03**	n.a
4		20	**5116.40±71.77**	n.a
5		40	5670.60±144.45	**5379.00**
6	90	9	3173.55±44.33	**3011.00**
7		10	**3962.30±26.81**	n.a
8		15	**3952.25±72.52**	n.a
9		18	**4336.70±43.92**	n.a
10		30	**4586.15±68.85**	n.a
11	100	5	3947.05±17.11	**3891.00**
12		10	**4118.25±44.28**	n.a
13		20	**4004.95±73.81**	n.a
14		25	**5955.70±61.02**	n.a
15		50	7459.10 ±118.47	**7253.00**

References

[1] B. Xin, Y. P. Wang, J. Chen, An efficient marginal-return-based constructive heuristic to solve the sensor-weapon-target assignment problem, IEEE Transactions on Systems, Man, and Cybernetics: Systems (2018) 1–12doi:10.1109/TSMC.2017.2784187.

[2] Y. H. Feng, G. G. Wang, S. Deb, M. Lu, X. J. Zhao, Solving 0-1 knapsack problem by a novel binary monarch butterfly optimization, Neural Computing and Applications 28 (7) (2017) 1619–1634. doi:10.1007/s00521-015-2135-1.

[3] A. E. Ezugwu, V. Pillay, D. Hirasen, K. Sivanarain, M. Govender, A comparative study of meta-heuristic optimization algorithms for 0-1 knapsack problem: Some initial results, IEEE Access 7 (2019) 43979–44001. doi:10.1109/ACCESS.2019.2908489.