

# 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](https://github.com/luzaijiaoxia/SWEVO_supplementary_file)).

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## 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.

### 5 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

10 2.

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**Algorithm 1** Random initialization for STSCF/MTSCF

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```
1: for  $s = 1$  to  $N_p$  do
2:   for  $i = 1$  to  $n$  do
3:     if  $rand < 0.5$  ( $rand \in (0, 1)$ ) then
4:       The agent  $a_i$  joins the coalition  $C$ .
5:     end if
6:   end for
7:   Add the coalition into the initial population  $P_{ini}$ .
8: end for
```

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**Algorithm 2** Decremental heuristic initialization for STSCF/MTSCF

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

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### 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.

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**Algorithm 3** Hybrid repair strategy for STSCF/MTSCF

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```
1: for  $s = 1$  to  $N_p$  do
2:   if the  $s$ th coalition  $C$  is an infeasible solution then
3:     Compute the remaining requirement on the  $j$ th ability of the task
      $R_t^j = \min\{q_t^j - q_c^j, 0\}$  ( $j \in \{1, 2, \dots, r\}$ ), the sum of the  $j$ th ability of every
     unassigned agent  $R_B^j = \sum_{a_i \in R_A} b_i^j$  ( $j \in \{1, 2, \dots, r\}$ ), the set of the unassigned
     agents  $R_A$  ( $R_A \cup C = A$  and  $R_A \cap C = \emptyset$ ).
4:     repeat
5:       if  $rand < \gamma$  ( $rand \in (0, 1)$ ) then
6:         Randomly select an agent  $a_i$  ( $a_i \in R_A$ ) to join the  $s$ th coalition
          $C$ .
7:       else
8:         Compute the value  $f_i = (\sum_{j=1}^r \frac{R_t^j}{R_B^j} \times b_i^j) / d_i$  ( $a_i \in R_A$ ).
9:         Select the agent  $a_i$  ( $a_i \in R_A$ ) which has the maximum value
         of  $f_i$  to join the coalition.
10:      end if
11:      Update  $R_A$ ,  $R_t^j$  and  $R_B^j$  ( $j \in \{1, 2, \dots, r\}$ ).
12:    until the coalition  $C$  becomes a feasible solution.
13:  end if
14: end for
```

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## 15 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,  
20 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-

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**Algorithm 4** Random initialization for MTMCF

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

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**Algorithm 5** Decremental heuristic initialization for MTMCF

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```
1: for  $s = 1$  to  $N_p$  do
2:   Add the coalition into the initial population  $P_{ini}$  generated by the ran-
   dom initialization in Algorithm 4.
3: end for
4: for  $s = 1$  to  $N$  do
5:   for  $k = 1$  to  $m$  do
6:     repeat
7:       Obtain a list  $S_A$  in which deleting any agent does not violate
       constraints in the current coalition  $C_k$ .
8:       Randomly delete an agent  $a_i$  ( $a_i \in S_A$ ).
9:     until there are not superfluous agents in the coalition  $C_k$ .
10:   end for
11: end for
```

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tion does not violate the constraints. The detail of the decremental heuristic  
25 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 a-  
gents to the coalitions which do not satisfy the ability requirements of the cor-

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**Algorithm 6** Hybrid repair strategy for MTMCF

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```

1: for  $s = 1$  to  $N_p$  do
2:   Initialize the set of the unassigned agents  $R_A$ , the remaining require-
      ment on the  $j$ th ability of the  $k$ th task  $R_{t_k}^j = \min\{p_{t_k}^j - p_{c_k}^j, 0\}$  ( $k \in$ 
       $\{1, 2, \dots, m\}$ ,  $j \in \{1, 2, \dots, r\}$ ), the sum of the  $j$ th ability of every unas-
      signed agent  $R_B^j = \sum_{a_i \in R_A} b_i^j$  ( $j \in \{1, 2, \dots, r\}$ ).
3:   if there exists a coalition  $C_k$  of the  $s$ th individual is infeasible then
4:     repeat
5:       if  $rand < \gamma$  ( $rand \in (0, 1)$ ) then
6:         Randomly select an agent  $a_i$  ( $a_i \in R_A$ ) to join any coalition
          $C_k$  ( $k \in \{1, 2, \dots, m\}$ ) which does not satisfy the task constraints.
7:       else
8:         Compute the value  $s_k^j = \frac{R_{t_k}^j}{R_B^j}$ ,  $f_k^i =$ 
           $\sum_{j=1}^r (\frac{s_k^j}{\sum_{j=1}^r s_k^j} \times b_i^j) / d_i$  ( $a_i \in R_A$ ).
9:         Select the agent  $a_i$  to join the coalition  $C_k$  which has the
          maximum value of  $f_k^i$ .
10:      end if
11:      Update  $R_A$ ,  $R_{t_k}^j$  and  $R_B^j$  ( $k \in \{1, 2, \dots, m\}$ ,  $j \in \{1, 2, \dots, r\}$ ).
12:    until all coalitions  $C_k$  ( $\forall k \in \{1, 2, \dots, m\}$ ) satisfy the requirements
      of the corresponding tasks or  $R_A$  is an empty set.
13:   end if
14: end for

```

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responding tasks. The repair method is based on the heuristic rules in the  
 30 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
	$\alpha$	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 Wilcoxon's rank-sum tests

55 with the significance level of 0.05. One algorithm gets a point as long as the Wilcoxon's 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 $\pm$ 2.68	253.00 $\pm$ 0.00
2	1320.35 $\pm$ 13.34	1314.60 $\pm$ 8.31
3	708.80 $\pm$ 26.63	<b>686.05 <math>\pm</math> 17.45</b>
4	3929.90 $\pm$ 27.61	<b>3912.15 <math>\pm</math> 0.37</b>
5	9157.15 $\pm$ 72.92	<b>9085.80 <math>\pm</math> 77.34</b>
6	8572.70 $\pm$ 207.68	<b>7754.80 <math>\pm</math> 212.61</b>
7	10320.10 $\pm$ 241.92	<b>9264.65 <math>\pm</math> 261.39</b>
8	17774.25 $\pm$ 194.92	<b>17003.25 <math>\pm</math> 394.93</b>
9	17952.65 $\pm$ 325.58	<b>15730.15 <math>\pm</math> 359.33</b>
10	10701.60 $\pm$ 496.26	<b>7709.60 <math>\pm</math> 338.13</b>
11	28904.30 $\pm$ 358.77	<b>27413.05 <math>\pm</math> 596.25</b>
12	38716.35 $\pm$ 324.75	<b>38192.50 <math>\pm</math> 235.74</b>
Score	0	<u><b>10</b></u>

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

60 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

65 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 $\pm$ 0.00	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00
2	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00
3	669.35 $\pm$ 6.04	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00
4	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00
5	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00
6	7148.80 $\pm$ 4.70	7146.00 $\pm$ 0.00	7146.00 $\pm$ 0.00	7146.00 $\pm$ 0.00
7	8306.70 $\pm$ 4.50	8302.35 $\pm$ 1.93	8302.20 $\pm$ 1.96	8304.30 $\pm$ 1.49
8	15348.25 $\pm$ 8.49	15340.40 $\pm$ 6.17	15340.75 $\pm$ 4.89	15343.85 $\pm$ 3.76
9	13274.40 $\pm$ 7.74	13265.55 $\pm$ 3.00	13263.00 $\pm$ 0.00	13263.00 $\pm$ 0.00
10	5875.25 $\pm$ 3.39	5873.90 $\pm$ 2.17	5880.35 $\pm$ 4.20	5883.20 $\pm$ 4.01
11	23753.90 $\pm$ 7.76	23752.70 $\pm$ 6.41	23753.55 $\pm$ 4.97	23757.10 $\pm$ 1.41
12	33839.85 $\pm$ 6.19	33836.70 $\pm$ 4.57	33838.05 $\pm$ 4.73	33845.30 $\pm$ 3.26
Score	22	50	46	28
No.	GAHIR-II-PF	GAHIR-II-RR	GAHIR-II-HY	GAHIR-II-HR
1	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00
2	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00
3	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00
4	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00
5	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00
6	7146.00 $\pm$ 0.00	7146.00 $\pm$ 0.00	7146.00 $\pm$ 0.00	7146.00 $\pm$ 0.00
7	8300.15 $\pm$ 0.67	8300.00 $\pm$ 0.00	8304.40 $\pm$ 1.82	8304.65 $\pm$ 1.84
8	15338.65 $\pm$ 2.56	15335.90 $\pm$ 2.17	15344.00 $\pm$ 4.27	15346.60 $\pm$ 2.84
9	13267.75 $\pm$ 3.99	13263.85 $\pm$ 1.57	13263.00 $\pm$ 0.00	13263.75 $\pm$ 1.55
10	5874.15 $\pm$ 3.03	5873.35 $\pm$ 2.23	5883.80 $\pm$ 3.30	5883.45 $\pm$ 3.15
11	23739.50 $\pm$ 5.41	23736.00 $\pm$ 0.00	23755.50 $\pm$ 3.07	23757.85 $\pm$ 0.67
12	33834.00 $\pm$ 0.00	33834.00 $\pm$ 0.00	33834.00 $\pm$ 0.00	33834.00 $\pm$ 0.00
Score	67	77	36	30
No.	GAHIR-DI-PF	GAHIR-DI-RR	GAHIR-DI-HY	GAHIR-DI-HR
1	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00
2	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00
3	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00
4	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00
5	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00
6	7148.10 $\pm$ 3.75	7146.00 $\pm$ 0.00	7146.00 $\pm$ 0.00	7146.00 $\pm$ 0.00
7	8307.90 $\pm$ 5.17	8301.70 $\pm$ 2.05	8302.70 $\pm$ 2.00	8304.90 $\pm$ 1.02
8	15348.65 $\pm$ 8.98	15339.40 $\pm$ 6.26	15341.20 $\pm$ 3.61	15344.35 $\pm$ 4.04
9	13275.45 $\pm$ 7.09	13265.75 $\pm$ 3.32	13263.00 $\pm$ 0.00	13263.40 $\pm$ 1.23
10	5876.70 $\pm$ 3.51	5874.10 $\pm$ 2.34	5878.75 $\pm$ 4.80	5881.85 $\pm$ 4.68
11	23751.80 $\pm$ 7.69	23750.65 $\pm$ 9.08	23753.80 $\pm$ 2.24	23757.25 $\pm$ 1.33
12	33844.55 $\pm$ 7.04	33838.10 $\pm$ 5.30	33836.40 $\pm$ 4.38	33845.80 $\pm$ 0.89
Score	20	47	51	22
No.	GAHIR-HI-PF	GAHIR-HI-RR	GAHIR-HI-HY	GAHIR-HI-HR
1	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00	253.00 $\pm$ 0.00
2	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00	1310.00 $\pm$ 0.00
3	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00	668.00 $\pm$ 0.00
4	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00	3912.00 $\pm$ 0.00
5	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00	8889.00 $\pm$ 0.00
6	7183.40 $\pm$ 21.13	7146.00 $\pm$ 0.00	7146.00 $\pm$ 0.00	7146.00 $\pm$ 0.00
7	8320.00 $\pm$ 0.00	8305.60 $\pm$ 1.35	8305.10 $\pm$ 1.02	8305.25 $\pm$ 1.48
8	15402.10 $\pm$ 9.16	15339.00 $\pm$ 0.00	15336.20 $\pm$ 3.69	15337.80 $\pm$ 4.29
9	13382.25 $\pm$ 35.68	13283.90 $\pm$ 9.16	13266.55 $\pm$ 3.22	13266.95 $\pm$ 2.98
10	5878.00 $\pm$ 0.00	5878.00 $\pm$ 0.00	5877.35 $\pm$ 2.06	5877.60 $\pm$ 1.79
11	23822.30 $\pm$ 15.28	23768.30 $\pm$ 3.37	23756.80 $\pm$ 4.14	23755.90 $\pm$ 2.20
12	33920.70 $\pm$ 13.88	33857.80 $\pm$ 0.89	33853.75 $\pm$ 3.73	33845.35 $\pm$ 8.15
Score	6	23	32	31



70 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

75 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.  
80 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  
85 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  
90 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  
95 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.

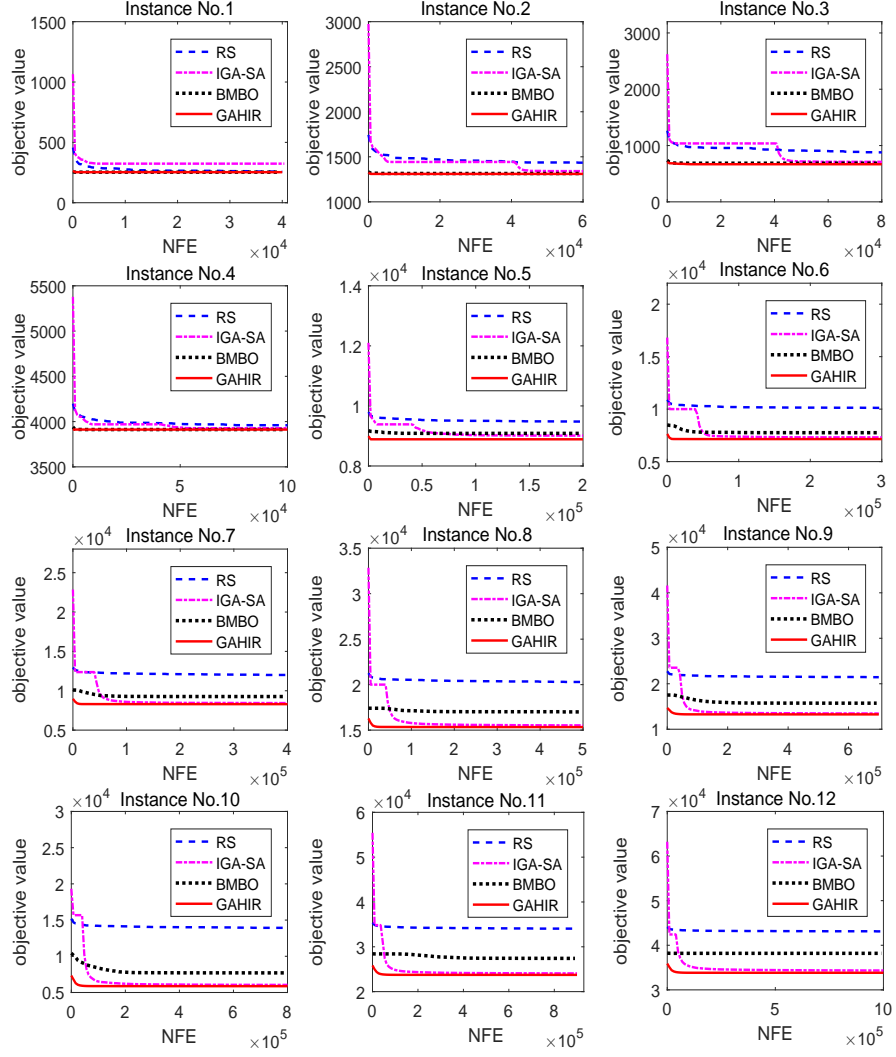


Figure 1: Convergence curves of GAHIR, IGA-SA, BMBO and RS for STSCF

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	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>
2	841.90 $\pm$ 15.98	<b>834.30</b> $\pm$ <b>8.06</b>	<b>832.10</b> $\pm$ <b>4.92</b>	<b>831.00</b> $\pm$ <b>0.00</b>
3	807.24 $\pm$ 17.86	<b>794.00</b> $\pm$ <b>0.00</b>	<b>794.00</b> $\pm$ <b>0.00</b>	<b>794.00</b> $\pm$ <b>0.00</b>
4	1451.35 $\pm$ 18.64	<b>1440.30</b> $\pm$ <b>9.91</b>	<b>1443.00</b> $\pm$ <b>11.21</b>	1460.20 $\pm$ 7.80
5	1522.30 $\pm$ 93.82	1345.90 $\pm$ 34.19	1309.25 $\pm$ 20.92	<b>1286.00</b> $\pm$ <b>14.65</b>
6	2660.23 $\pm$ 222.36	<b>2083.40</b> $\pm$ <b>19.50</b>	<b>2076.00</b> $\pm$ <b>10.08</b>	<b>2078.60</b> $\pm$ <b>11.63</b>
7	2143.45 $\pm$ 50.01	2061.05 $\pm$ 30.34	2030.80 $\pm$ 24.61	<b>2016.50</b> $\pm$ <b>13.27</b>
8	3432.45 $\pm$ 91.81	3210.95 $\pm$ 55.77	3144.35 $\pm$ 35.85	<b>3095.85</b> $\pm$ <b>39.34</b>
9	4634.97 $\pm$ 273.58	2982.85 $\pm$ 87.33	<b>2892.55</b> $\pm$ <b>59.38</b>	<b>2883.45</b> $\pm$ <b>37.59</b>
10	3205.55 $\pm$ 96.64	3030.45 $\pm$ 56.51	2952.55 $\pm$ 46.02	<b>2906.70</b> $\pm$ <b>29.38</b>
11	3755.95 $\pm$ 113.31	3326.80 $\pm$ 89.75	3184.90 $\pm$ 66.31	<b>3126.10</b> $\pm$ <b>49.30</b>
12	8795.46 $\pm$ 769.01	5703.55 $\pm$ 113.72	<b>5580.55</b> $\pm$ <b>137.15</b>	<b>5532.00</b> $\pm$ <b>99.82</b>
13	4427.40 $\pm$ 81.93	4239.90 $\pm$ 66.88	<b>4127.90</b> $\pm$ <b>40.35</b>	<b>4106.20</b> $\pm$ <b>42.95</b>
14	4947.80 $\pm$ 222.39	4270.00 $\pm$ 112.55	4030.90 $\pm$ 68.32	<b>3981.00</b> $\pm$ <b>90.88</b>
15	12701.29 $\pm$ 1051.79	7773.20 $\pm$ 223.35	<b>7525.05</b> $\pm$ <b>113.95</b>	<b>7435.20</b> $\pm$ <b>122.17</b>
Score	9	62	103	109
No.	GAHIR-II-PF	GAHIR-II-RR	GAHIR-II-HY	GAHIR-II-HR
1	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>
2	844.65 $\pm$ 16.90	<b>834.00</b> $\pm$ <b>9.59</b>	<b>831.00</b> $\pm$ <b>0.00</b>	<b>831.00</b> $\pm$ <b>0.00</b>
3	<b>795.00</b> $\pm$ <b>4.45</b>	<b>794.00</b> $\pm$ <b>0.00</b>	<b>794.00</b> $\pm$ <b>0.00</b>	<b>794.00</b> $\pm$ <b>0.00</b>
4	1464.40 $\pm$ 20.43	1460.70 $\pm$ 12.91	1449.00 $\pm$ 13.44	1456.55 $\pm$ 10.34
5	1503.05 $\pm$ 79.79	1353.75 $\pm$ 50.62	<b>1291.35</b> $\pm$ <b>20.92</b>	<b>1291.25</b> $\pm$ <b>17.91</b>
6	2504.16 $\pm$ 218.45	2086.75 $\pm$ 18.40	<b>2076.00</b> $\pm$ <b>10.02</b>	<b>2079.50</b> $\pm$ <b>13.38</b>
7	2128.60 $\pm$ 36.76	2053.00 $\pm$ 29.62	<b>2013.95</b> $\pm$ <b>23.62</b>	<b>2018.90</b> $\pm$ <b>12.03</b>
8	3340.45 $\pm$ 86.97	3190.00 $\pm$ 50.62	3148.30 $\pm$ 37.54	<b>3120.35</b> $\pm$ <b>41.16</b>
9	4037.10 $\pm$ 359.21	3048.05 $\pm$ 83.87	2928.45 $\pm$ 77.60	<b>2892.25</b> $\pm$ <b>66.23</b>
10	3181.90 $\pm$ 84.51	3014.40 $\pm$ 52.81	2944.05 $\pm$ 38.67	2906.85 $\pm$ 14.67
11	3634.00 $\pm$ 139.81	3305.85 $\pm$ 101.97	<b>3159.80</b> $\pm$ <b>70.58</b>	<b>3125.30</b> $\pm$ <b>66.67</b>
12	8492.24 $\pm$ 760.16	5675.40 $\pm$ 162.85	5625.35 $\pm$ 151.98	<b>5549.05</b> $\pm$ <b>126.50</b>
13	4380.00 $\pm$ 52.71	4242.00 $\pm$ 51.33	<b>4131.30</b> $\pm$ <b>52.07</b>	<b>4124.80</b> $\pm$ <b>24.52</b>
14	4687.25 $\pm$ 154.49	4183.55 $\pm$ 77.97	<b>4021.40</b> $\pm$ <b>89.93</b>	<b>3992.55</b> $\pm$ <b>59.85</b>
15	11511.73 $\pm$ 653.48	7684.50 $\pm$ 176.87	<b>7493.15</b> $\pm$ <b>128.67</b>	<b>7497.60</b> $\pm$ <b>121.56</b>
Score	18	52	98	103
No.	GAHIR-DI-PF	GAHIR-DI-RR	GAHIR-DI-HY	GAHIR-DI-HR
1	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>
2	840.00 $\pm$ 14.80	<b>833.20</b> $\pm$ <b>6.77</b>	<b>832.90</b> $\pm$ <b>8.50</b>	<b>831.00</b> $\pm$ <b>0.00</b>
3	800.25 $\pm$ 15.18	<b>794.00</b> $\pm$ <b>0.00</b>	<b>794.00</b> $\pm$ <b>0.00</b>	<b>794.00</b> $\pm$ <b>0.00</b>
4	1453.15 $\pm$ 14.63	<b>1440.00</b> $\pm$ <b>11.89</b>	<b>1441.60</b> $\pm$ <b>12.44</b>	1460.75 $\pm$ 8.85
5	1538.05 $\pm$ 69.04	1375.90 $\pm$ 56.21	1302.70 $\pm$ 24.57	<b>1291.35</b> $\pm$ <b>20.92</b>
6	2684.75 $\pm$ 244.10	2090.00 $\pm$ 20.35	<b>2077.30</b> $\pm$ <b>10.67</b>	<b>2075.05</b> $\pm$ <b>9.75</b>
7	2156.65 $\pm$ 45.34	2065.80 $\pm$ 30.98	<b>2015.35</b> $\pm$ <b>31.88</b>	<b>2014.50</b> $\pm$ <b>20.42</b>
8	3473.30 $\pm$ 104.95	3189.70 $\pm$ 47.69	3153.30 $\pm$ 49.62	<b>3108.90</b> $\pm$ <b>38.62</b>
9	4509.95 $\pm$ 421.56	3003.55 $\pm$ 110.05	2926.35 $\pm$ 48.81	<b>2902.60</b> $\pm$ <b>53.86</b>
10	3197.10 $\pm$ 72.41	3022.45 $\pm$ 41.12	2928.20 $\pm$ 33.69	<b>2896.30</b> $\pm$ <b>13.41</b>
11	3758.95 $\pm$ 162.99	3304.50 $\pm$ 77.67	<b>3157.85</b> $\pm$ <b>61.02</b>	<b>3117.00</b> $\pm$ <b>64.41</b>
12	9285.69 $\pm$ 757.95	5713.60 $\pm$ 221.14	<b>5517.75</b> $\pm$ <b>94.60</b>	<b>5562.25</b> $\pm$ <b>108.96</b>
13	4478.05 $\pm$ 91.40	4225.30 $\pm$ 46.16	<b>4134.25</b> $\pm$ <b>34.69</b>	<b>4118.25</b> $\pm$ <b>44.28</b>
14	4963.60 $\pm$ 163.54	4280.65 $\pm$ 99.86	4051.85 $\pm$ 89.28	<b>4004.95</b> $\pm$ <b>73.81</b>
15	12852.69 $\pm$ 1209.37	7857.50 $\pm$ 187.55	<b>7494.10</b> $\pm$ <b>143.04</b>	<b>7459.10</b> $\pm$ <b>118.47</b>
Score	7	62	100	<b>110</b>
No.	GAHIR-HI-PF	GAHIR-HI-RR	GAHIR-HI-HY	GAHIR-HI-HR
1	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>	<b>493.00</b> $\pm$ <b>0.00</b>
2	844.70 $\pm$ 13.55	<b>831.00</b> $\pm$ <b>0.00</b>	<b>831.00</b> $\pm$ <b>0.00</b>	<b>831.00</b> $\pm$ <b>0.00</b>
3	796.07 $\pm$ 4.70	<b>794.00</b> $\pm$ <b>0.00</b>	<b>794.00</b> $\pm$ <b>0.00</b>	<b>794.00</b> $\pm$ <b>0.00</b>
4	1462.30 $\pm$ 5.98	1459.60 $\pm$ 9.34	1450.30 $\pm$ 14.61	1461.15 $\pm$ 6.96
5	1488.55 $\pm$ 68.27	1372.50 $\pm$ 66.47	1301.75 $\pm$ 27.28	<b>1298.55</b> $\pm$ <b>32.35</b>
6	2696.96 $\pm$ 157.90	2086.50 $\pm$ 12.92	<b>2077.25</b> $\pm$ <b>10.59</b>	<b>2077.45</b> $\pm$ <b>13.13</b>
7	2092.75 $\pm$ 32.15	2044.85 $\pm$ 27.45	<b>2016.90</b> $\pm$ <b>14.97</b>	<b>2011.70</b> $\pm$ <b>14.07</b>
8	3314.10 $\pm$ 65.87	3173.55 $\pm$ 59.29	3147.05 $\pm$ 49.24	<b>3106.60</b> $\pm$ <b>31.82</b>
9	3888.95 $\pm$ 139.38	3055.10 $\pm$ 99.01	<b>2899.10</b> $\pm$ <b>52.26</b>	<b>2896.90</b> $\pm$ <b>50.46</b>
10	3202.40 $\pm$ 90.31	3020.90 $\pm$ 48.30	2924.65 $\pm$ 28.94	2913.50 $\pm$ 28.27
11	3693.40 $\pm$ 100.89	3283.10 $\pm$ 59.56	3168.25 $\pm$ 68.31	<b>3119.90</b> $\pm$ <b>52.36</b>
12	7952.89 $\pm$ 270.85	5657.10 $\pm$ 107.39	<b>5550.85</b> $\pm$ <b>103.74</b>	<b>5522.60</b> $\pm$ <b>82.94</b>
13	4389.40 $\pm$ 59.14	4216.70 $\pm$ 36.91	<b>4133.40</b> $\pm$ <b>41.97</b>	<b>4125.95</b> $\pm$ <b>41.19</b>
14	4551.35 $\pm$ 77.21	4184.90 $\pm$ 86.06	4068.10 $\pm$ 96.70	<b>3980.10</b> $\pm$ <b>70.77</b>
15	11374.71 $\pm$ 375.11	7745.60 $\pm$ 152.58	<b>7538.85</b> $\pm$ <b>130.87</b>	<b>7449.95</b> $\pm$ <b>136.04</b>
Score	19	54	101	<b>110</b>

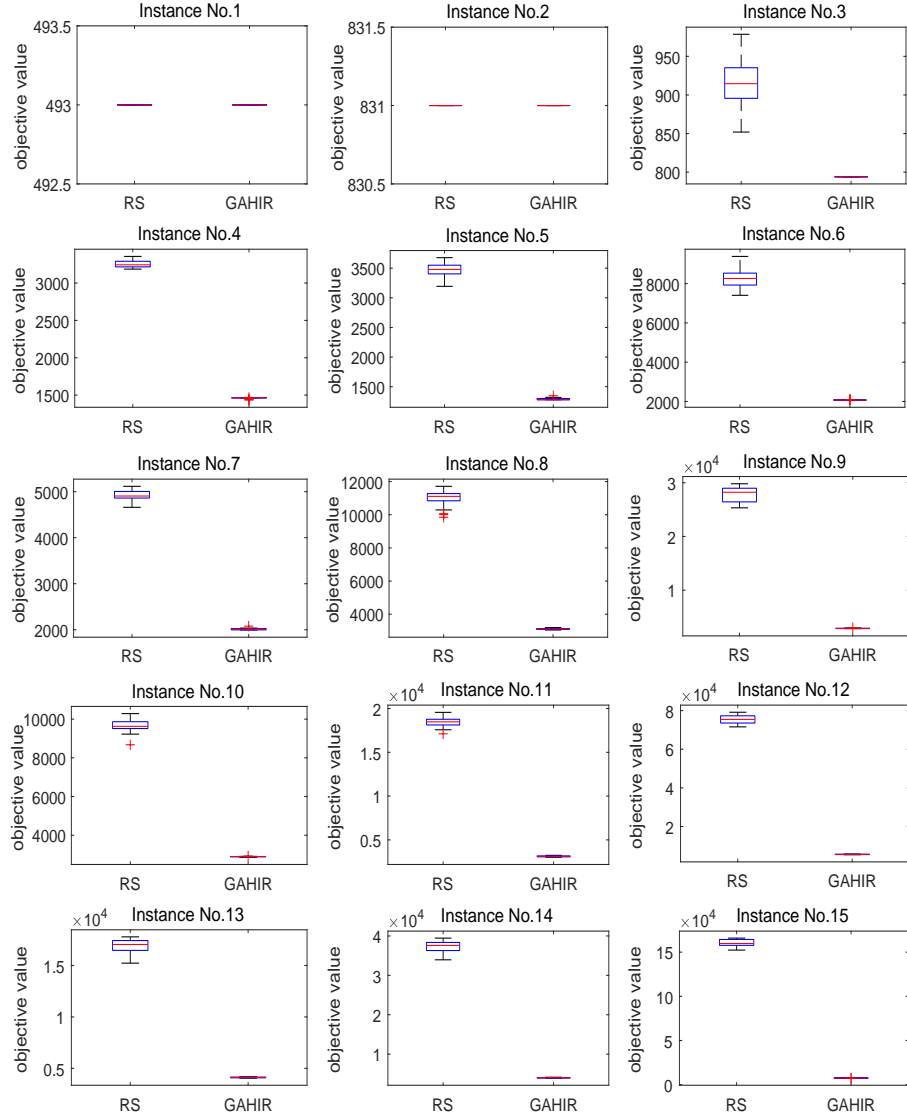


Figure 2: Box plots of GAHIR and RS for MTMCF

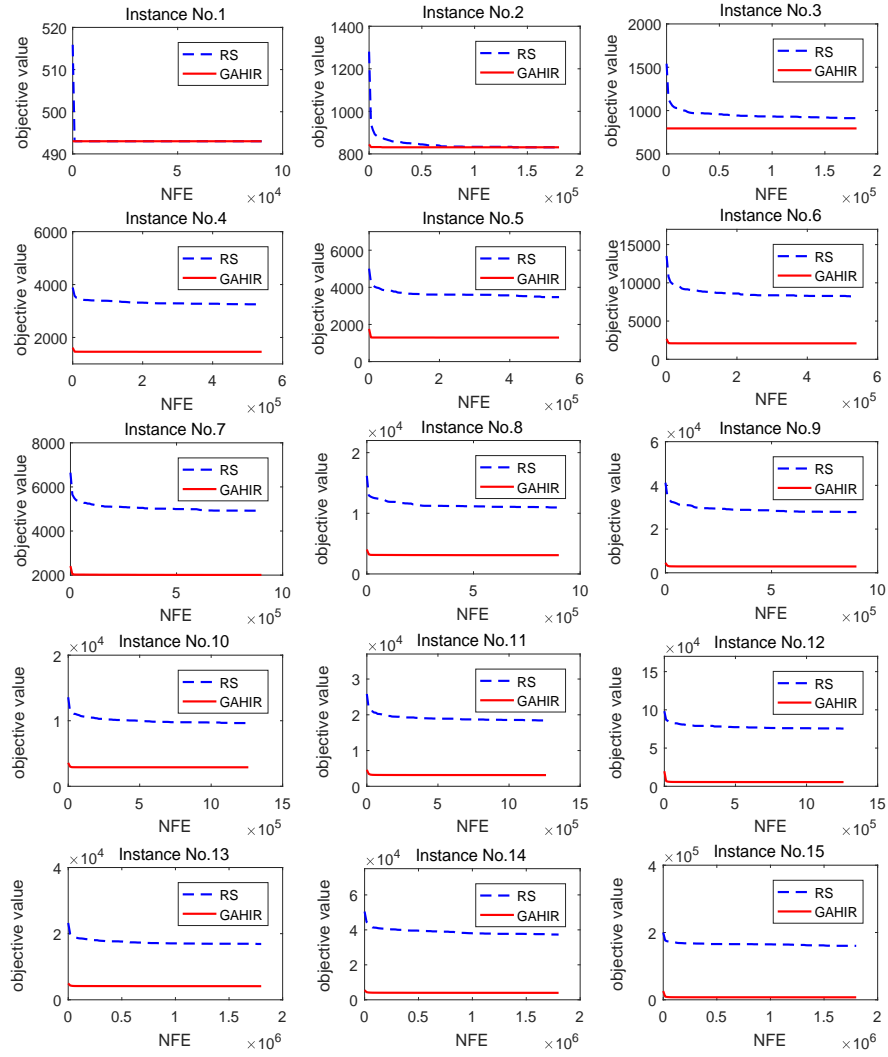


Figure 3: Convergence curves of GAHIR and RS for MTMCF

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

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

## References

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