Soft Comput
DOI 10.1007/s00500-012-0957-7

Optimal job scheduling in grid computing using efficient binary artificial bee colony optimization

Sung-Soo Kim · Ji-Hwan Byeon · Hongbo Liu · Ajith Abraham · Seán McLoone

Abstract The artificial bee colony has the advantage of employing fewer control parameters compared with other population-based optimization algorithms. In this paper a binary artificial bee colony (BABC) algorithm is developed for binary integer job scheduling problems in grid computing. We further propose an efficient binary artificial bee colony extension of BABC that incorporates a flexible ranking strategy (FRS) to improve the balance between exploration and exploitation. The FRS is introduced to generate and use new solutions for diversified search in early generations and to speed up convergence in latter generations. Two variants are introduced to minimize the makepsan. In the first a fixed number of best solutions is employed with the FRS while in the second the number of the best solutions is reduced with each new generation. Simulation results for benchmark job scheduling problems show that the performance of our proposed methods is better than those alternatives such as genetic algorithms, simulated annealing and particle swarm optimization.

Communicated by F. Herrera.

S.-S. Kim · J.-H. Byeon
Department of Industrial Engineering, Kangwon National University, Chunchon 200-701, Korea
e-mail: kimss@kangwon.ac.kr

J.-H. Byeon
e-mail: benjy86@nate.com

H. Liu (✉)
School of Information Science and Technology, Dalian Maritime University, Dalian 116026, China
e-mail: lhb@dlut.edu.cn

H. Liu
Institute for Neural Computation, University of California San Diego, La Jolla, CA 92093, USA

A. Abraham
Machine Intelligence Research Labs, Scientific Network for Innovation and Research Excellence, Auburn, WA 98071, USA
e-mail: ajith.abraham@ieee.org

A. Abraham
IT For Innovations - Center of Excellence, VSB - Technical University of Ostrava, Ostrava - Poruba 708 33, Czech Republic

S. McLoone
Department of Electronic Engineering, National University of Ireland Maynooth, Maynooth, Kildare, Ireland
e-mail: sean.mcloone@eeng.nuim.ie

Keywords Artificial bee colony (ABC) · Binary artificial bee colony (BABC) · Efficient binary artificial bee colony (EBABC) · Flexible ranking strategy (FRS) · Job scheduling · Grid computing

1 Introduction

A computational grid is a large scale, heterogeneous collection of autonomous systems, geographically distributed and interconnected by low-latency and high-bandwidth networks (Foster and Kesselman 2004). It provides the underlying infrastructure for the rapidly growing field of cloud computing (Foster et al. 2008; Wei and Blake 2010). The sharing of computational jobs is a major application for grids. In a computational grid, resources are dynamic and diverse and can be added and withdrawn at any time at the owner's discretion, and their performance or load can change frequently over time. Grid resource management provides functionality for the discovery and publishing of resources as well as scheduling, submission and monitoring of jobs. Scheduling is a particularly challenging problem as

Published online: 20 November 2012

it is known to be NP-complete (Garey and Johnson 1979). Dong and Akl (2006) provide a detailed analysis of the scheduling problem as it pertains to the grid.

Swarm intelligence is an innovatively distributed intelligent paradigm whereby the intelligence that emerges in nature from the collective behaviours of unsophisticated individuals interacting locally with their environment is exploited to develop optimization algorithms that identify optimum solutions efficiently in complex search spaces (Bonabeau et al. 1999; Kennedy et al. 2001; Liu et al. 2007). Within this paradigm algorithms have been developed that mimic swarming behaviours observed in flocks of birds, schools of fish, or swarms of bees, colonies of ants and even human social behaviour, from which intelligence is seen to emerge (Clerc 2006; Walker 2007; Forestiero et al. 2008; Su et al. 2009; Banks et al. 2009; Singh and Sundar 2011; Yang 2011; Cuevas et al. 2012; Abraham et al. 2012; Yue et al. 2012). Recently, these algorithms have been investigated as a means of efficiently estimating optimal job allocation on computational grids in application-level scheduling (Abraham et al. 2008; Izakian et al. 2010; Liu et al. 2010).

In this paper we introduce the efficient binary artificial bee colony (EBABC) algorithm as an enhancement of the binary artificial bee colony (BABC) algorithm (Pampara and Engelbrecht 2011; Chandrasekaran et al. 2012) for solving the makespan minimization problem in grid computing job scheduling (an NP-complete problem). We demonstrate theoretically that the proposed algorithm converges with a probability of 1 towards the global optimal and with the aid of benchmark job scheduling problems illustrate its operation and performance.

The rest of the paper is organized as follows: Section 2 describes related work on swarm intelligence based approaches to optimal job scheduling. Section 3 deals with some theoretical foundations related to job scheduling in grid computing. In Sect. 4, we describe the proposed EBABC algorithm in detail. Experimental results and analysis are then presented in Sect. 5 and finally conclusions are presented in Sect. 6.

2 Related work

The job scheduling problem has attracted the attention of researchers worldwide, not only because of its practical and theoretical importance, but also because of its complexity. It is a NP-complete optimization problem (Garey and Johnson 1979; Brucker 2007; Liu et al. 2009; Pinedo 2012). Different approaches have been proposed to solve this problem. Bruker and Schlie (1990) illustrated a polynomial algorithm for solving job shop scheduling problems with two jobs. Mastrolilli and Gambardella (1999) introduced a solution graph representation of the problem and developed a local tabu search-based algorithm to identify new solutions in the neighbourhood of existing solutions. Jansen et al. (2000) provided a linear time approximation scheme for problems where the number of machines and the maximum number of operations per job are fixed. Because of the intractable nature of the problem and its importance in practical applications, it is desirable to explore other avenues for developing heuristic algorithms.

Braun et al. (2001) investigated 11 static heuristics for the job scheduling that try to capture different degrees of heterogeneity of grid resources and workload of jobs and resources. This study compared the techniques using a set of simulated scheduling problems defined in terms of expected time to compute (ETC) matrices and provided insights into circumstances where one technique outperforms another. Genetic algorithms (GA) were investigated for job scheduling in grid computing by Di Martino and Mililotti (2004), Gao et al. (2005) and Xhafa et al. (2007). They used the benchmark job scheduling problems introduced by Braun et al. (2001) to verify their proposed method. They considered 12 different types of ETC matrices.

Liu et al. (2010) proposed fuzzy particle swarm optimization (FPSO) and verified the performance of particle swarm optimization (PSO) compared with GA and simulated annealing (SA). Their FPSO approach to scheduling jobs on computational grids is based on using fuzzy matrices to represent the position and velocity of the particles in PSO. Abraham et al. (2008) and Izakian et al. (2010) proposed the discrete particle swarm optimization (DPSO) algorithm for job scheduling in grid computing. Laalaoui and Drias (2010) present an ant colony optimization (ACO) algorithm to search for feasible schedules of real-time tasks on identical processors. A learning technique is introduced to detect and postpone possible preemptions between tasks. Ritchie and Levine (2003, 2004) applied local search, the ant algorithm combined with local and tabu search for scheduling independent jobs in grid computing. They demonstrate that the hybrid ant algorithm can find shorter schedules on benchmark problems than local search, tabu search or genetic algorithms. In Izakian's paper (Izakian et al. 2010), the scheduler seeks to minimize makespan in the grid environment. They compare their DPSO with GA, ACO, continuous particle swarm optimization (CPSO) and FPSO using 12 ETC matrices for 512 jobs and 16 machines (Braun et al. 2001) to illustrate that their proposed method is more efficient. Xiao et al. (2012) proposed a hybrid approach for solving the multi-mode resource-constrained multi-project scheduling problem, in which the labour division feature of ACO is employed to establish a task priority scheduling model and improved particle swarm optimization is used to identify the optimum scheduling scheme. Vivekanandan et al. (2011)

developed an artificial bee colony (ABC) algorithm for grid computing to reduce the makespan and showed that it outperformed ACO.

The job scheduling problem in grid computing is similar to the multiprocessor scheduling problem (MSP). Hou et al. (1994) used genetic algorithms for multiprocessor scheduling. They assume that the multiprocessor system is uniform and non-preemptive, that is, the processors are identical, and a processor completes the current task before executing a new one. Davidovic et al. (2009) used bee colony optimization for multiprocessor systems. They also assume that the problem of static scheduling has independent tasks on homogeneous multiprocessors (identical processors). The survey paper by Davis and Burns (2011) covers research into hard real-time scheduling for homogeneous multiprocessor systems. The grid computing job scheduling problem considered in this paper is one of allocating independent jobs to different grids (different processors in MSP). There are more specific papers of state-of-art for MSPs (Thesen 1998; Fujita and Yamashita 2000; Wu et al. 2004).

Pan et al. (2011) proposed a discrete implementation of the basic ABC algorithm so that it could be used to solve the lot-streaming flow shop scheduling problem. They developed a population initialization method and discrete implementations of the three phases of ABC operation (represented by employed bees, onlooker bees and scout bees) for their discrete artificial bee colony (DABC) algorithm. Ziarati et al. (2011) developed a bee algorithm, artificial bee colony and bee swarm optimization for the resource constrained project scheduling problem (RCPSP). They considered the applicability of the bee methods for RCPSP. Wong et al. (2010) investigated an improved bee colony optimization algorithm with Big Valley landscape exploitation (BCBV) to solve the job shop scheduling problem. The BCBV algorithm mimics the bee foraging behaviour where information of a newly discovered food source is communicated via waggle dances. Li et al. (2011) proposed a hybrid Pareto-based artificial bee colony (HABC) algorithm for solving the multi-objective flexible job shop scheduling problem to balance the exploration and exploitation capability.

Sharma and Pant (2011) proposed intermediate ABC (I-ABC) by suggesting some modifications to the structure of basic ABC to further improve its performance. Bao and Zeng (2009) proposed and compared disruptive selection, tournament selection and rank selection strategies for avoiding premature convergence of ABC to local optima. Alzaqebah and Abdullah (2011) compared three selection strategies (i.e. disruptive, tournament and rank) with the not proportional selection strategy used by onlooker bees in the original ABC. Mezura-Montes and Velez-Koeppel (2010) proposed an elitist artificial bee colony for constrained real-parameter optimization by generating more diverse and convenient solutions using three types of bees (employed, onlooker and scout). However, a critical disadvantage of this method is that it increases the number of parameters that need to be determined. Lee and Cai (2011) proposed a diversity strategy to resolve the problem of premature convergence and difficulties escaping local optima for the improved ABC algorithm. The main consideration with ABC like heuristic algorithms is how to achieve the correct balance between exploration for diversified search and exploitation for convergence to the optimal solution.

3 Job scheduling in grid computing

In the computational grid environment, there is usually a general framework focusing on the interaction between a grid resource broker, domain resource manager and the grid information server (Abraham et al. 2000). Computational grids usually assume that the physical and virtual levels are completely split with a mapping existing between resources and users of the two layers (Nemeth and Sunderam 2003). Han and Berry (2008) proposed a novel semantic-supported and agent-based decentralized grid resource discovery mechanism. Without overhead of negotiation, the algorithm allows individual resource agents to semantically interact with neighbour agents based on local knowledge and to dynamically form a resource service chain to complete the tasks. Chung and Chang (2009) presented a Grid Resource Information Monitoring (GRIM) prototype to manage resources for dynamic access, resource management in a large-scale grid environment. In a grid environment it is usually easy to obtain information about the speed of the available grid nodes but quite challenging to determine the computational processing time requirements of the user. To conceptualize the problem as an algorithm, we need to dynamically estimate the job lengths from user application specifications or historical data (Liu et al. 2010).

Some key terminologies associated with job scheduling in grid computing are discussed in Liu et al. (2010). Here, we explain only the terminology relevant to our objective problems. A grid node (computing unit) is a set of computational resources with limited capacities. A job is considered as a single set of multiple atomic operations/tasks. A schedule is the mapping of the tasks to specific time intervals on the grid nodes. Consider J_j $(j \in \{1, 2, \ldots, N\})$ independent user jobs on G_i $(i \in \{1, 2, \ldots, M\})$ heterogeneous grid nodes and an overall objective of scheduling the jobs so as to minimize the completion time. The speed of each node is expressed as the number of Cycles Per Unit Time (CPUT) and the length of each job as the number of cycles. Each job J_j has its processing requirement (cycles) and the node G_i has its calculating speed (cycles/second).

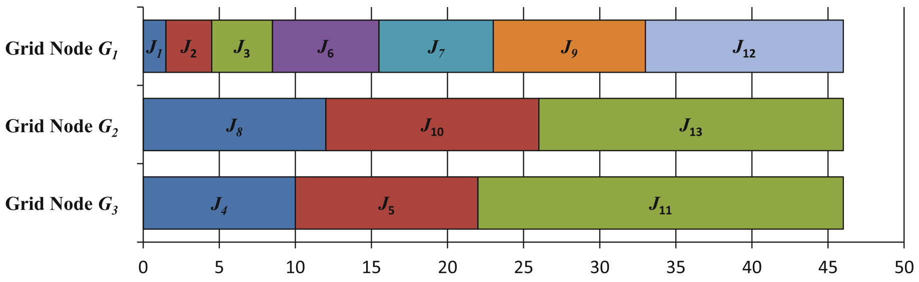


Fig. 1 The scheduling solution for (3, 13)

Individual jobs J_j must be processed until completion on a single grid node. To formulate our objective, we define C_{ij} as the time it takes grid node G_i to complete job J_j. We use an $M \times N$ binary matrix $X = x_{ij}$ to denote decision variables, with $x_{ij} = 1$ if job j is assigned to grid node i and $x_{ij} = 0$ otherwise. As mentioned above, scheduling is an NP-complete problem. Generally assumptions are made to simplify, formulate and solve scheduling problems. We also comply with the most common assumptions:

- a successor job is performed immediately after its predecessor is finished (provided the machine is available);
- each machine can handle only one job at a time;
- each job can only be performed on one machine at a time;
- there is no interruption of jobs or reworking once they have been processed successfully;
- setup and transfer times are zero or have uniform duration;
- jobs are independent.

The time required to complete the processing of all jobs for a given schedule X is known as the "makespan", MS. Since all grid nodes begin computing at the same time, the schedule completion time is determined by the grid node that has the longest processing time for all the jobs assigned to it; hence

$$MS(X) = \max_{i \in 1,2,\ldots,M} \sum_{j=1}^{N} C_{ij} \times x_{ij} \tag{1}$$

The objective of the binary integer programming problem is to determine the schedule X that minimizes the makespan $MS(X)$ while satisfying the schedule feasibility constraints, that is,

$$Y^* = \min_X MS(X) \tag{2}$$

subject to

$$x_{ij} = \begin{cases} 1 & \text{if job } j \text{ is assigned to grid node } i \\ 0 & \text{otherwise.} \end{cases}$$
$$\sum_{i=1}^{M} x_{ij} = 1 \quad \forall j \tag{3}$$

An optimal schedule will be one that optimizes the makespan. For example, the jobs J_1, J_2, J_3, J_6, J_7, J_9 and J_{12} are allocated on grid node 1 in Fig. 1, $C_{1,1} = 1.5$, $C_{1,2} = 3$, $C_{1,3} = 4$, $C_{1,6} = 7$, $C_{1,7} = 7.5$, $C_{1,9} = 10$ and $C_{1,12} = 13$. For grid node 1, the single node flowtime $\sum_{j=1}^{N} C_{1j} = 46$. The other two grid node flowtimes are also 46. So the makespan is 46 in the schedule solution.

4 Efficient binary artificial bee colony for job scheduling

In this section, we introduce the EBABC for solving job scheduling problems. First, the basic artificial bee colony (ABC) is summarized. Then the BABC is developed for job scheduling in grid computing. The efficient BABC algorithm (EBABC) is presented as an extension of BABC incorporating a flexible ranking strategy to improve performance. We also prove that the proposed algorithm converges with a probability of 1 towards the global optimum.

4.1 Artificial bee colony

The ABC is an algorithm motivated by the intelligent behaviour exhibited by honeybees when searching for food. The performance of ABC is better than or similar to other population-based algorithms with the added advantage of employing fewer control parameters (Ma et al. 2011; Li et al. 2012). The only important control parameter for ABC is *Limit*; the number of unsuccessful trials before a food source is deemed to be abandoned (Karaboga and Akay 2009; Karaboga and Basturk 2007, 2008). The main steps of the basic ABC algorithm are summarized in Algorithm 1 (Karaboga and Akay 2009).

In ABC, the colony of artificial bees contains three groups of bees: employed bees, onlooker bees and scout bees. For every food source (FS) there is only one employed bee. A fitness function is used to assign a quality or 'nectar' value to the food sources. Each employed bee searches for a new food source within its own neighbourhood and moves to it if it has a higher nectar value. Employed bees then share their food source information (location and nectar value) with the onlooker bees waiting in the hive. Each onlooker bee then selects one of the employed bee food sources probabilistically in a process similar to roulette wheel selection, The probability assigned to the kth food source, P_k, is given by

Table 1 An optimal schedule for (3,13)

Grid node	Job												
	J_1	J_2	J_3	J_4	J_5	J_6	J_7	J_8	J_9	J_{10}	J_{11}	J_{12}	J_{13}
G_1	1	1	1	0	0	1	1	0	1	0	0	1	0
G_2	0	0	0	0	0	0	0	1	0	1	0	0	1
G_3	0	0	0	1	1	0	0	0	0	0	1	0	0

$$P_k = \frac{\frac{1}{f_k}}{\sum_{i=1}^{SN} \frac{1}{f_i}} \tag{4}$$

where f_k is the nectar value of the kth food source and SN is the total number of food sources (=Number of employed bees). After selecting its food source each onlooker bee then seeks out one new food source within its neighbourhood and moves to this food source if it has a higher nectar value. If the number of active food sources outnumbers the maximum allowed, those with the lowest nectar values are abandoned. An employed bee for a food source that has been abandoned becomes a scout bee and starts to search for a new food source randomly. Thus, while onlooker bees and employed bees are targeted at exploitation, scout bees provide a mechanism for exploration (Karaboga and Basturk 2008).

Algorithm 1 ABC Algorithm

```
1: Initialization.
2: Employed bees initially select their food sources randomly,
   and then search locally for a better food source.
3: Onlooker bees choose their food sources in the neighbourhood
   of probabilistically selected employed bee food sources. The
   selection probability is proportional to the food source nectar
   value, as given by Equ. (4).
4: Scout bees search for new food sources randomly.
5: At the end of each cycle the best food source found so far is
   memorized.
6: If termination criteria are not satisfied, the algorithm is re-
   peated from Step 2; otherwise the algorithm terminates and
   outputs the best food source found.
```

4.2 Binary artificial bee colony

The BABC algorithm is formulated in this section for application to job scheduling in grid computing. A job scheduling solution can be represented as shown in Table 1. If the job j is assigned to grid node i, then "1" is assigned. Otherwise, "0" is assigned. This corresponds to encoding a food source as a matrix X defined in accordance with the constraints given in Eq. (3). The matrix for Table 1 has 3 $\times$ 13 elements, hence the search space has 39 dimensions.

The BABC has the following steps:

1. The algorithm begins by setting the *Limit* (maximum number of unsuccessful trials when searching for an improved food source in the vicinity of an active food source) and SN (number of active food sources, employed bees and onlooker bees) parameters and initializing the population of food sources (solutions) assigned to the employed bees randomly using the binary solution representation for job scheduling. For example, one grid node is selected randomly from grid nodes 1, 2 and 3 for each job as shown in Table 1.
2. The initial population of food sources is evaluated using the makespan objective function $MS(X)$, as defined in Eq. (1). Each food source k is then assigned a score or nectar value $f_k = MS(X_k)$.
3. *Employed bees* New candidate solutions are then generated in the neighbourhood of existing solutions by swapping any two randomly selected jobs (whole columns in X) in the current solutions (one for each employed bee). For example, by swapping the randomly selected jobs J_4 (0 0 1) and job J_8 (0 1 0) for the solution shown in Table 1 a new neighbourhood solution is obtained. If the two randomly selected jobs are the same, then the random selection process is repeated.
4. *Employed bees* A greedy selection process is applied to update the food sources assigned to the employed bees, that is, for each employed bee, if its candidate neighbourhood food source is better than its existing one the employed bee adopts the new food source. This is noted by setting the trial count variable *Trial* for that food source to "0". Otherwise, if the employed bee does not change its food source the trial count is incremented by 1.
5. *Onlooker bees* Each onlooker bee selects one of the employer bee food sources probabilistically based on the nectar values of the food sources. The food source selection probabilities are computed according to Eq. (4).
6. *Onlooker bees* Each onlooker then generates a new solution (food source) by swapping any two randomly selected columns of their selected food sources. If the new food source has a higher nectar value than the existing food source, the corresponding employed bee updates it position to the new food source and sets the food source trial count variable *Trial* to "0". Otherwise, the employed bee does not change its food source and the trial count is incremented by 1.
7. *Scout bees* If the *Trial* count for a food source (employed bee) exceeds the value defined by *Limit*, the food source is abandoned and the corresponding employed bee becomes a scout bee and generates a new food source (solution) randomly.
8. Finally, the best solution identified by the swarm is memorized and the algorithm repeats from step 3 until a predetermined termination criterion is met.

4.3 Efficient binary artificial bee colony

A weakness of the BABC algorithm is that the new randomly generated solutions by the scout bees in general have poorer quality compared with existing solution groups

Table 2 Makespan of 20 food sources for initial population

Food source number	1	2	3	4	5	6	7	8	9	10
Makespan	50.67	51.33	54	51	51	51	51.5	50.67	52	54
Food source number	11	12	13	14	15	16	17	18	19	20
Makespan	50.5	55.33	50	52	55	50	54.67	51	50.67	55

identified by the employee and onlooker bees. Even though the generation of random solutions is desirable for exploration purposes the overall performance of the algorithm can be impacted as the number of these solutions is increased. In order to solve this problem and to generate new solutions whose quality is not significantly different from existing solutions we propose a modification to the BABC algorithm involving a flexible ranking strategy (FRS). The resulting algorithm, referred to as the EBABC algorithm, is summarized in Algorithm 2. Steps 1 to 10 of EBABC correspond to steps 1 to 6 of the BABC algorithm as described in the previous section. The new FRS step is introduced between step 6 and 7 of the BABC algorithm and proceeds as follows:

– FRS step The food sources of the employed bee population are arranged in order of ascending nectar value (Makespan). Then the worst solution in the population is removed and a new solution is generated probabilistically as a combination of the best RSN solutions in the population. The probability of selecting a job from the kth solution among the RSN best solutions is computed as

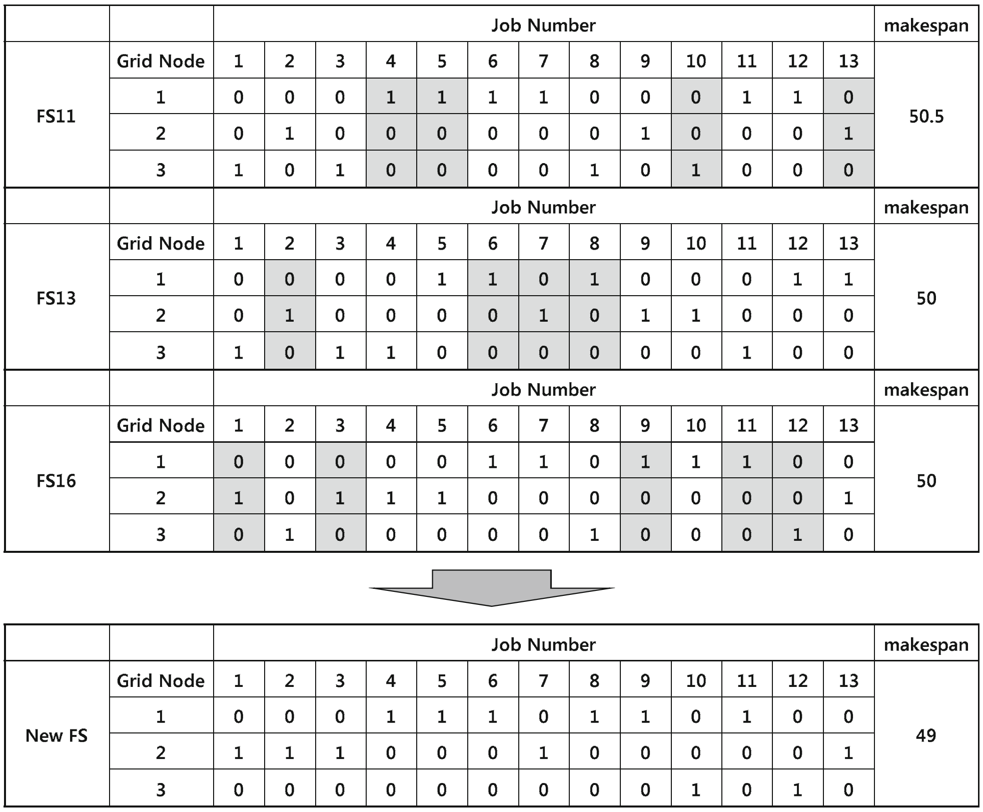
$$P_k = \frac{\frac{1}{f_k}}{\sum_{i=1}^{\mathrm{RSN}} \frac{1}{f_i}} \tag{5}$$

As an example of the operation of FRS, consider a population of 20 food sources with makespans (nectar values) as given in Table 2. If RSN = 3 the three best food sources in the population (i.e. FS_{11}, FS_{13} and FS_{16}) are used to generate a new food source as shown in Fig. 2. The probability of selecting each job for the new food source FS from these three sources is computed according to Eq. (5) as follows:

$$P(\mathrm{FS}_{11}) = \frac{1}{50.5} \bigg/ \left\{ \frac{1}{50.5} + \frac{1}{50} + \frac{1}{50.5} \right\} = 0.3311$$
$$P(\mathrm{FS}_{13}) = \frac{1}{50} \bigg/ \left\{ \frac{1}{50.5} + \frac{1}{50} + \frac{1}{50.5} \right\} = 0.3344$$
$$P(\mathrm{FS}_{16}) = \frac{1}{50} \bigg/ \left\{ \frac{1}{50.5} + \frac{1}{50} + \frac{1}{50.5} \right\} = 0.3344$$

As shown in Fig. 2, based on these probabilities jobs 4, 5, 10 and 13 in FS are selected from FS_{11}, jobs 2, 6, 7 and 8 are selected from FS_{13} and jobs 1, 3, 9, 11 and 12 are selected from FS_{16}. The complete columns for each job in the new solution are copied from FS_{11}, FS_{13} and FS_{16}, ensuring that the resulting new FS is a feasible solution.

Two approaches to selecting RSN (the number of the best solutions to be used in FRS) are considered. In the first



		Job Number													makespan
FS11	Grid Node	1	2	3	4	5	6	7	8	9	10	11	12	13	50.5
	1	0	0	0	1	1	1	1	0	0	0	1	1	0	
	2	0	1	0	0	0	0	0	0	1	0	0	0	1	
	3	1	0	1	0	0	0	0	1	0	1	0	0	0	

		Job Number													makespan
FS13	Grid Node	1	2	3	4	5	6	7	8	9	10	11	12	13	50
	1	0	0	0	0	1	1	0	1	0	0	0	1	1	
	2	0	1	0	0	0	0	1	0	1	1	0	0	0	
	3	1	0	1	1	0	0	0	0	0	0	1	0	0	

		Job Number													makespan
FS16	Grid Node	1	2	3	4	5	6	7	8	9	10	11	12	13	50
	1	0	0	0	0	0	1	1	0	1	1	1	0	0	
	2	1	0	1	1	1	0	0	0	0	0	0	0	1	
	3	0	1	0	0	0	0	0	1	0	0	0	1	0	

		Job Number													makespan
New FS	Grid Node	1	2	3	4	5	6	7	8	9	10	11	12	13	49
	1	0	0	0	1	1	1	0	1	1	0	1	0	0	
	2	1	1	1	0	0	0	1	0	0	0	0	0	1	
	3	0	0	0	0	0	0	0	0	0	1	0	1	0	

Fig. 2 New food source (FS) representation and generation of new food source using FRS with RSN = 3

approach, referred to as EBABC1, RSN is a user-defined constant value which can be optimized experimentally. In the second approach, referred to as EBABC2, a new value of RSN is calculated at each generation G, according to

$$\mathrm{RSN} = \mathrm{Max}\left(\lceil SN \times \alpha^{G} \rceil, \mathrm{RSN}_{\mathrm{Min}}\right) \tag{6}$$

Here, $\mathrm{RSN}_{\mathrm{Min}}$ is a lower bound on the number of best solutions to be used with FRS, α is a real number greater than 0 and less than 1, $\lceil SN \times \alpha^{G} \rceil$ denotes rounding up to the nearest integer and the Max() function returns the maximum value of its arguments.

The advantage of EBABC2 is that in early generations the new food source is generated using all *SN* food sources in the swarm thereby improving the diversity of the search, while in later generations only the few best solutions are used improving the convergence of the algorithm.

It should be noted that EBABC1 and EBABC2 are not guaranteed to converge to an optimal solution. However, our experiments show that both methods are able to identify better job scheduling solution than those obtained in earlier studies.

4.4 Convergence analysis

To analyse the convergence of the algorithm we first introduce some definitions and lemmas (Guo and Tang 2001; He et al. 2005; Chung and Erdös1952) and then theoretically prove that our EBABC algorithm converges with probability 1 (or strongly) to the global optimum.

Consider the problem (P):

$$(P) = \begin{cases} \min f(\mathbf{x}) \\ \mathbf{x} \in \Omega = [-s, s]^n \end{cases} \tag{7}$$

where $\mathbf{x} = (x_1, x_2, \ldots, x_n)^T$. Denoting $\mathbf{x}^*$ as the global optimal solution to the problem (P), s as the limit of the solution space and $f^* = f(\mathbf{x}^*)$, we can define

$$D_0 = \{\mathbf{x} \in \Omega | f(\mathbf{x}) - f^* < \varepsilon\} \tag{8}$$

$$D_1 = \Omega \setminus D_0$$

for every $\varepsilon > 0$.

As described above, the algorithm produces new solutions by swapping any two randomly selected columns of jobs. Let u be a uniformly distributed random number in the interval $[-s, s]$, and η a positive constant scaling factor that controls the domain of oscillation in the solution space. Therefore, the oscillation of the new solution $\hat{s}$ is uniformly distributed. During the iterated procedure from time t to $t+1$, let q_{ij} denote that $\mathbf{x}(t) \in D_i$ and $\mathbf{x}(t+1) \in D_j$. Accordingly, the positions of food sources in the colony can be assigned to one of four states: q_{00}, q_{01}, q_{10} and q_{01}. Obviously $q_{00} + q_{01} = 1$, $q_{10} + q_{11} = 1$.

Algorithm 2 EBABC with Flexible Ranking Strategy (FRS) Algorithm

```
1: Initialize the population of job scheduling solutions $X_k, k = 1, 2, \cdots, SN$, using the binary solution representation and assign an employed bee to each solution
2: Evaluate the nectar values of the population using Equ. (1)
3: $cycle \leftarrow 1$
4: repeat
5:    Produce new solutions by swapping any two randomly selected columns of the current $X$ associated with each employed bee and evaluate them using Equ. (1)
6:    If the new solutions are better than the existing ones, replace them with the new ones, otherwise, $Trial \leftarrow Trial + 1$
7:    Calculate the onlooker selection probability values for the employee bee solutions using Equ. (4)
8:    Assign employee bee solutions to the onlooker bees based on their selection probabilities using roulette wheel selection and evaluate their nectar values using Equ. (1)
9:    Produce new onlooker solutions by swapping any two randomly selected columns in the solution representation $X$ and evaluate them using Equ. (1)
10:   If the new solutions are better than old ones, update to the new one. Otherwise, $Trial \leftarrow Trial + 1$
      {// Start of Flexible Ranking Strategy (FRS) Step}
11:   do
12:      Evaluate all employed bee solutions using Equ. (1)
13:      Sort the solutions in ascending order
14:      Determine the value of $RSN$ for the current generation
15:      if EBABC1 is true, then
16:         $RSN$ is an a priori fixed value (determined experimentally).
17:      end if
         or
18:      if EBABC2 is true, then
19:         $RSN$ is defined for the current generation according to Equ. (6).
20:      end if
21:      Remove the worst solution in the employed bee population and replace it with a new solution generated by selecting jobs from each of the best $RSN$ solutions in the population, with a selection probability given by Equ. (5)
      {// End of Flexible Ranking Strategy (FRS) Step}
22:   Determine the food sources that are to be abandoned, i.e where $Trial > Limit$, and reassign the corresponding employed bees as scout bees
23:   For each scout bee generate a new food source (solution) randomly.
24:   Memorize the best solution achieved so far
25:   $cycle \leftarrow cycle + 1$
26: until $cycle = MCN$
```

Definition 1 (*Convergence in terms of probability*) Let ξ_n be a sequence of random variables, and ξ a random variable, all defined on the same probability space. The sequence ξ_n converges with a probability of ξ if

$$\lim_{n\to\infty} P(|\xi_n - \xi| < \varepsilon) = 1 \tag{9}$$

for every $\varepsilon > 0$.

Definition 2 (*Convergence with a probability of 1*) Let ξ_n be a sequence of random variables, and ξ a random variable, all defined on the same probability space. The sequence ξ_n converges almost surely or almost everywhere or with probability 1 or strongly to ξ if

$$P\left(\lim_{n\to\infty} \xi_n = \xi\right) = 1; \tag{10}$$

or

$$P\left(\bigcap_{n=1}^{\infty} \bigcup_{k\geq n} [|\xi_n - \xi| \geq \varepsilon]\right) = 0 \tag{11}$$

for every $\varepsilon > 0$.

Lemma 1 (Borel-Cantelli Lemma) *Let* $\{A_k\}_{k=1}^{\infty}$*be a sequence of events occurring with a certain probability distribution, and letAbe the event consisting of the occurrences of a finite number of events*A_k *for* $k = 1, 2, \ldots$*.Then*

$$P\left(\bigcap_{n=1}^{\infty} \bigcup_{k\geq n} A_k\right) = 0 \tag{12}$$

if

$$\sum_{n=1}^{\infty} P(A_n) < \infty; \tag{13}$$

and

$$P\left(\bigcap_{n=1}^{\infty} \bigcup_{k\geq n} A_k\right) = 1 \tag{14}$$

if the events are totally independent and

$$\sum_{n=1}^{\infty} P(A_n) = \infty. \tag{15}$$

Theorem 1 (Bee State Transference) $q_{01} = 0$; $q_{00} = 1$; $q_{11} \leq c \in (0,1)$*and* $q_{10} \geq 1 - c \in (0,1)$.

Proof In the algorithm, the best solution is updated and saved during the complete iterated procedure. So $q_{01} = 0$ and $q_{00} = 1$. Let $\hat{\mathbf{x}}$ be the position with the best fitness identified by the colony up to and including time t. In accordance with Eq. (8), $\exists\ r > 0$, when $\|\mathbf{x} - \hat{\mathbf{x}}\|_\infty \leq r$, we have $|f(\mathbf{x}) - f^*| < \varepsilon$. Denote $Q_{\hat{\mathbf{x}},r} = \{x \in \Omega | \|\mathbf{x} - \hat{\mathbf{x}}\|_\infty \leq r\}$. Accordingly

$$Q_{\hat{\mathbf{x}},r} \subset D_0 \tag{16}$$

Then

$$\begin{aligned} P\{(\mathbf{x} + \Delta\mathbf{x}) \in Q_{\hat{\mathbf{x}},r}\} &= \prod_{i=1}^{n} P\{|x_i + \Delta x_i - \hat{x}_i| \leq r\} \\ &= \prod_{i=1}^{n} P\{\hat{x}_i - x_i - r \leq \Delta x_i \leq \hat{x}_i - x_i + r\} \end{aligned} \tag{17}$$

where x_i, Δx_i and $\hat{x}_i$ are the i-th dimensional values of $\mathbf{x}$,$\Delta\mathbf{x}$ and $\hat{\mathbf{x}}$, respectively. Moreover, $\hat{s} \sim U[-\frac{s}{\eta}, \frac{s}{\eta}]$, so that

$$P((\mathbf{x} + \Delta\mathbf{x}) \in Q_{\hat{\mathbf{x}},r}) = \prod_{i=1}^{n} \int_{\hat{x}_i - x_i - r}^{\hat{x}_i - x_i + r} \frac{\eta}{2s} \tag{18}$$

Denote $P_1(\mathbf{x}) = P\{(\mathbf{x} + \Delta\mathbf{x}) \in Q_{\hat{\mathbf{x}},r}\}$ and $\mathbb{C}$ is the convex closure of the level set for the initial bee colony. According to Eq. (18), $0 < P_1(\mathbf{x}) < 1$ $(\mathbf{x} \in \mathbb{C})$. Again, since $\mathbb{C}$ is a bounded closed set, $\exists\hat{\mathbf{y}} \in \mathbb{C}$,

$$P_1(\hat{\mathbf{y}}) = \min_{\mathbf{x}\in\mathbb{C}} P_1(\mathbf{x}), \quad 0 < P_1(\hat{\mathbf{y}}) < 1. \tag{19}$$

Combining Eqs. (16) and (19) gives

$$q_{10} \geq P_1(\mathbf{x}) \geq P_1(\hat{\mathbf{y}}) \tag{20}$$

Let $c = 1 - P_1(\hat{\mathbf{y}})$; thus,

$$q_{11} = 1 - q_{10} \leq 1 - P_1(\hat{\mathbf{y}}) = c \quad (0 < c < 1) \tag{21}$$

and

$$q_{10} \geq 1 - c \in (0,1) \tag{22}$$

□

Theorem 2 *Assume that the EBABC algorithm provides a series of solution positions* $\mathbf{p}_i(t)(i = 1, 2, \ldots, n)$*at timetby the iterated procedure. Let* $\mathbf{p}^*$*be the best position in the colony explored so far, i.e.,.*

$$\mathbf{p}^*(t) = arg \min_{1\leq i\leq n} (f(\mathbf{p}^*(t-1)), f(\mathbf{p}_i(t))) \tag{23}$$

Then,

$$P\left(\lim_{t\to\infty} f(\mathbf{p}^*(t)) = f^*\right) = 1 \tag{24}$$

Proof For $\forall\varepsilon > 0$, let $p_k = P\{|f(\mathbf{p}^*(k)) - f^*| \geq \varepsilon\}$; then

$$p_k = \begin{cases} 0 & \text{if } \exists T \in \{1, 2, \ldots, k\}, \mathbf{p}^*(T) \in D_0 \\ \bar{p}_k & \text{if } \mathbf{p}^*(t) \notin D_0, t = 1, 2, \ldots, k \end{cases} \tag{25}$$

According to Theorem 1,

$$\bar{p}_k = P\{\mathbf{p}^*(t) \notin D_0, t = 1, 2, \ldots, k\} = q_{11}^k \leq c^k. \tag{26}$$

Hence,

$$\sum_{k=1}^{\infty} p_k \leq \sum_{k=1}^{\infty} c^k = \frac{c}{1-c} < \infty. \tag{27}$$

Table 3 Parameter settings for the algorithms

Algorithm	Parameter name	Parameter value	
		(3,13)	Other problems
BABC	Number of FS[a]	20	20
	Limit[b]	100	8000
EBABC1	Number of FS[a]	20	20
	Limit[b]	100	8000
	Number of FS[a] for FRS	3	3
EBABC2	Number of FS[a]	20	20
	Limit[b]	100	8000
	Persistency rate of Number of FS[a] for FRS(α)	0.99	0.999

[a] Food source

[b] Number of trials after which a food source is assumed to be abandoned

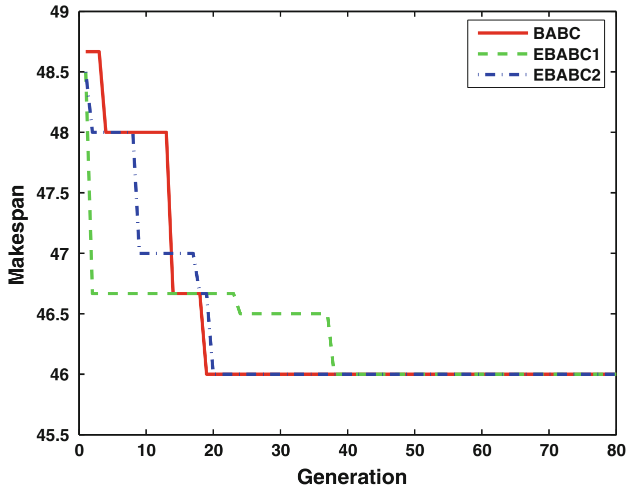


Fig. 3 Convergence trend for (3, 13) using BABC, EBABC1 and EBABC2

According to Lemma 1,

$$P\left(\bigcap_{t=1}^{\infty}\bigcup_{k\geq t}|f(\mathbf{p}^*(k))-f^*|\geq\varepsilon\right)=0 \tag{28}$$

Therefore, as defined in Definition 2, the sequence $f(\mathbf{p}^*(t))$ converges almost surely or almost everywhere or with probability 1 or strongly towards f^*. The theorem is proven. □

5 Experiments and analysis

5.1 Experimental settings

In the following sections we present experimental results for the BABC, EBABC1 and EBABC2 algorithms applied to a serious of benchmark job scheduling problems as defined

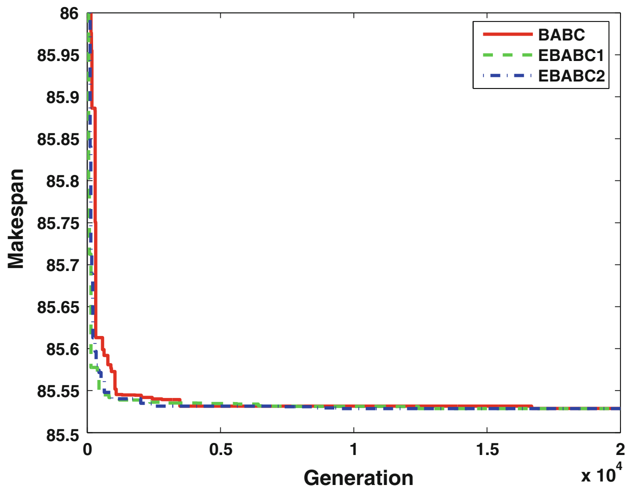


Fig. 4 Convergence trend for (5, 100) using BABC, EBABC1 and EBABC2

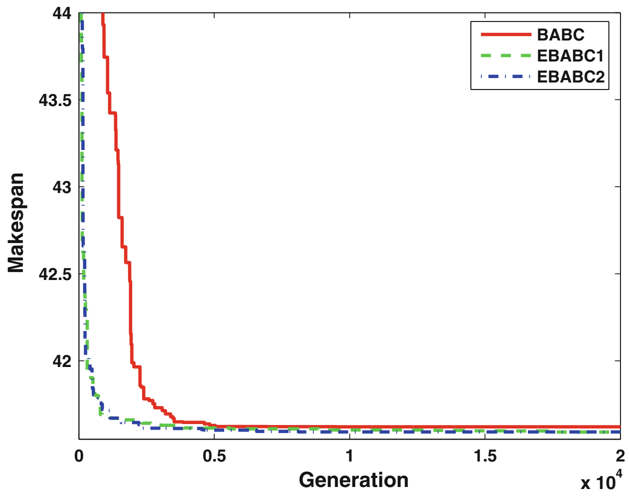


Fig. 5 Convergence trend for (8, 60) using BABC, EBABC1 and EBABC2

in Liu et al. (2010). The experiments were conducted on a desktop computer with an Intel® Core™2 Duo 2.66GHz CPU and 2G RAM. In total seven different dimensions of job scheduling problem were investigated, namely (3, 13), (5, 100), (8, 60), (10, 50), (10, 100), (60, 500) and (100, 1000). Here the notation (*G*, *J*) is employed to indicate the number of computing nodes on the grid (*G*) and number of jobs (*J*) to be scheduled for each problem. The specific parameter settings employed with BABC, EBABC1 and EBABC2 for each problem are given in Table 3.

5.2 Results and discussion

For the small scale job scheduling problem (3,13), the speeds of the three grid nodes are 4, 3 and 2 CPUT, and the

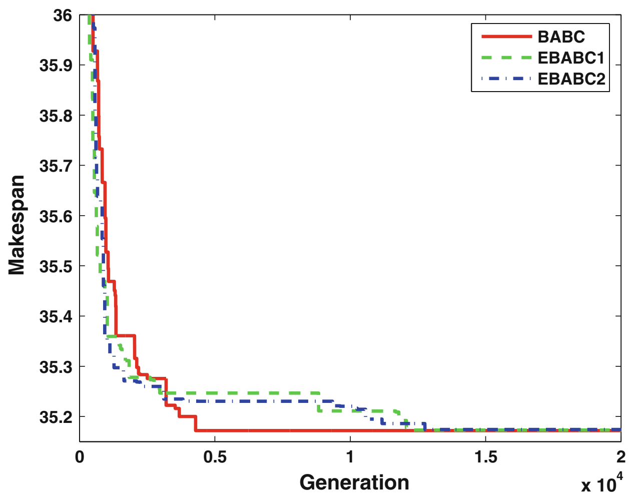


Fig. 6 Convergence trend for (10, 50) using BABC, EBABC1 and EBABC2

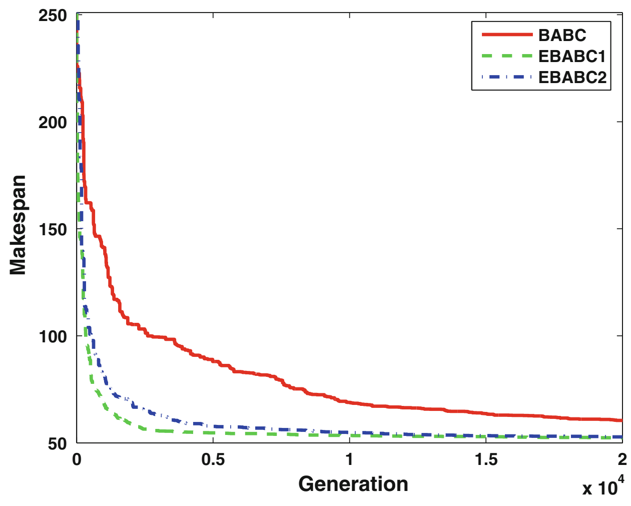


Fig. 8 Convergence trend for (60, 500) using BABC, EBABC1 and EBABC2

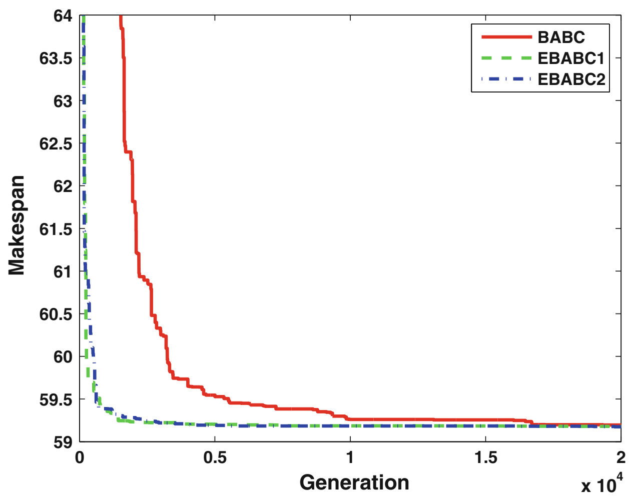


Fig. 7 Convergence trend for (10, 100) using BABC, EBABC1 and EBABC2

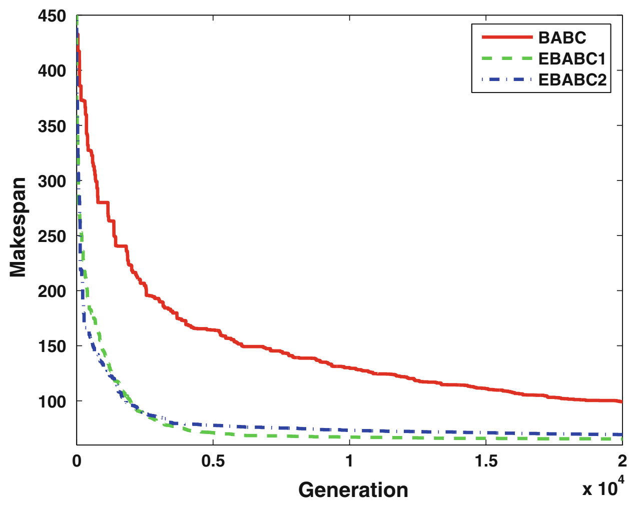


Fig. 9 Convergence trend for (100, 1000) using BABC, EBABC1 and EBABC2

job lengths of the 13 jobs are 6, 12, 16, 20, 24, 28, 30, 36, 40, 42, 48, 52 and 60 cycles. Figure 3 shows the convergence trend for job scheduling (3, 13) using BABC, EBABC1 and EBABC2. In the best job scheduling solution jobs 1, 2, 3, 6, 7, 9 and 12 are assigned to grid node 1, jobs 8, 10 and 13 are assigned to grid node 2 and the jobs 4, 5 and 11 are assigned to node 3 as shown in Fig. 1. The optimal makespan is 46. This is computed by dividing the total job length on each grid node by its speed and selecting the largest value. Thus, grid node 1 gives $(6 + 12 + 16 + 28 + 30 + 40 + 52)/4 = 46$, grid node 2 gives $(36 + 42 + 60)/3=46$ and grid node 3 gives $(20 + 24 + 48)/2 = 46$. Since all grid nodes have identical computation times this is the global optimum solution. All ten algorithm runs of BABC, EBABC1 and EBABC2 identify optimum solutions (makespan = 46) within 1000 generations. This compares to success rates of 2, 3 and 4 out of 10 runs within 2000 generations when using GA, SA and PSO as reported in Liu et al. (2010).

The performances of the BABC, EBABC1 and EBABC2 algorithms on the six larger job scheduling problems (i.e. (5,100), (8, 60), (10, 50), (10, 100), (60, 500) and (100,1000)) is summarized in Figs. 4, 5, 6, 7, 8 and 9.

The best solutions for the (5, 100), (8, 60) and (10, 50) job scheduling problems obtained with each algorithm are shown in Tables 4, 5 and 6, respectively. The corresponding optimal makespans are 85.5286 (using EBABC2), 41.5908 (using EBABC1) and 35.1718 (using BABC).

Table 4 Best solutions for job scheduling problem (5, 100) using EBABC2

Grid node	Assigned job number dataset
1	3, 13, 16, 26, 29, 35, 45, 47, 49, 53, 54, 57, 59, 60, 61, 63, 66, 67, 72, 77, 79, 83, 89, 92
2	8, 11, 15, 17, 20, 25, 30, 36, 69, 75, 94, 95
3	1, 4, 9, 12, 14, 18, 22, 33, 34, 37, 40, 43, 50, 64, 65, 68, 74, 80, 82, 88, 96, 99, 100
4	2, 7, 19, 21, 27, 28, 39, 42, 46, 48, 52, 56, 62, 73, 78, 81, 84, 85, 86, 93
5	5, 6, 10, 23, 24, 31, 32, 38, 41, 44, 51, 55, 58, 70, 71, 76, 87, 90, 91, 97, 98

Table 5 Best solutions for job scheduling problem (8, 60) using EBABC1

Grid node	Assigned job number dataset
1	14, 25, 28, 34, 40, 42, 45, 48, 49, 51, 59, 60
2	36, 38, 41, 44, 55
3	8, 11, 12, 16, 19, 21, 31, 35, 54, 58
4	5, 7, 17, 18, 26, 53, 57
5	1, 6, 9, 10, 13, 43, 47, 50
6	4, 24, 27, 30, 32, 33, 37, 52
7	2, 20, 22, 29, 39, 46, 56
8	3, 15, 23

Table 6 Best solutions for job scheduling problem (10, 50) using BABC

Grid node	Assigned job number dataset
1	11, 13, 18, 28, 31
2	12, 23, 37
3	1, 21, 26, 38, 45, 49
4	5, 16, 20, 24, 40, 41, 48
5	4, 10, 33, 39
6	3, 22, 35, 42
7	17, 19, 36, 46, 47
8	7, 15, 25, 27
9	6, 8, 9, 29, 30, 32, 34, 50
10	2, 14, 43, 44

The performance of BABC, EBABC1 and EBABC2 are compared in Tables 7, 8, 9 and 10 for four different instances of the seven benchmark problems as given in Liu et al. (2010). The notation P_{ij} is used to denote the jth instance of the ith problem. Here P_{1j} = (3, 13), P_{2j} = (5, 100), P_{3j} = (8, 60), P_{4j} = (10, 50), P_{5j} = (10, 100), P_{6j} = (60, 500) and P_{7j} = (100, 1000). The results show that EBABC1 and EBABC2 are similar to BABC for job scheduling problems (3, 13), (5,100), (8, 60), (10, 50) and (10, 100) are better than BABC for (60, 500) and substantially better than BABC for (100, 1000). This suggests that EBABC1 and EBABC2 are superior to BABC when the size of job scheduling problems is large enough.

Table 7 Performance comparison of BABC, EBABC1 and EBABC2 using Liu et al. (2010) data (P_{11}–P_{71})

P[a]	Algorithms	min[b]	$\bar{S}$[c]	σ[d]
P_{11}	BABC	46	46	0
	EBABC1	46	46	0
	EBABC2	46	46	0
P_{21}	BABC	85.5288	85.5303	0.0009
	EBABC1	85.5287	85.53	0.0008
	EBABC2	85.5286	85.5298	0.0006
P_{31}	BABC	41.6057	41.6179	0.0114
	EBABC1	41.5908	41.7287	0.3895
	EBABC2	41.592	41.5975	0.0028
P_{41}	BABC	35.1718	35.2031	0.026
	EBABC1	35.1729	35.2715	0.2599
	EBABC2	35.174	35.1896	0.0089
P_{51}	BABC	59.1846	59.2107	0.0505
	EBABC1	59.1768	59.1833	0.004
	EBABC2	59.1745	59.1815	0.0041
P_{61}	BABC	58.7357	61.0432	1.9377
	EBABC1	51.8877	53.4156	1.3144
	EBABC2	52.1308	52.9459	0.6648
P_{71}	BABC	91.5027	99.4408	5.6058
	EBABC1	65.1085	70.66	4.4817
	EBABC2	68.2587	71.0863	2.9236

[a] Scheduling problem
[b] Minimum
[c] Average
[d] Standard deviation

Finally, Table 11 provides a comparison between simulation results using EBABC2 and an earlier study by Liu et al. (2010) which evaluated genetic algorithm (GA), simulated annealing (SA) and particle swarm optimization (PSO) based job scheduling algorithms. The average value and standard deviation of the makespan achieved using EBABC2 are superior in all cases.

In order to assess the statistical significance of the performance differences between BABC, EBABC1 and EBABC2 as shown in Table 12 or between GA, SA, PSO and EBABC2 as shown in Table 13, the results were evaluated using the Kruskal–Wallis (1952) and Mann–Whitney (1947) tests. The Kruskal–Wallis test evaluates

Table 8 Performance comparison of BABC, EBABC1 and EBABC2 using P_{12}–P_{72}

P[a]	Algorithms	min[b]	$\bar{S}$[c]	σ[d]
P_{12}	BABC	84.7500	84.7750	0.0791
	EBABC1	84.7500	84.8750	0.1318
	EBABC2	84.7500	84.7750	0.0791
P_{22}	BABC	96.9140	96.9154	0.0008
	EBABC1	96.9141	96.9152	0.0006
	EBABC2	96.9139	96.9151	0.0008
P_{32}	BABC	35.8166	35.8281	0.0054
	EBABC1	35.8187	35.8247	0.0052
	EBABC2	35.8165	35.8216	0.0046
P_{42}	BABC	39.6781	39.7057	0.0177
	EBABC1	39.6712	39.6905	0.0198
	EBABC2	39.6741	39.6874	0.0144
P_{52}	BABC	68.6468	68.6854	0.0616
	EBABC1	68.6314	68.6439	0.0136
	EBABC2	68.6338	68.6384	0.0043
P_{62}	BABC	51.8034	53.3231	1.1443
	EBABC1	46.8856	48.5896	1.2013
	EBABC2	47.2847	48.4512	1.1581
P_{72}	BABC	91.5892	96.3269	3.4105
	EBABC1	68.2272	70.5031	1.9065
	EBABC2	70.0744	75.5895	4.3780

[a] Scheduling problem
[b] Minimum
[c] Average
[d] Standard deviation

Table 9 Performance comparison of BABC, EBABC1 and EBABC2 using P_{13}–P_{73}

P[a]	Algorithms	min[b]	$\bar{S}$[c]	σ[d]
P_{13}	BABC	77.2500	77.2500	0.0000
	EBABC1	77.2500	77.2667	0.0351
	EBABC2	77.2500	77.2583	0.0263
P_{23}	BABC	99.3544	99.3563	0.0011
	EBABC1	99.3545	99.3557	0.0007
	EBABC2	99.3550	99.3557	0.0005
P_{33}	BABC	35.3846	35.3961	0.0070
	EBABC1	35.3834	35.4925	0.3341
	EBABC2	35.3830	35.3878	0.0031
P_{43}	BABC	38.1283	38.1757	0.0387
	EBABC1	38.1237	38.1388	0.0133
	EBABC2	38.1313	38.1510	0.0167
P_{53}	BABC	63.1832	63.2041	0.0161
	EBABC1	63.1651	63.1731	0.0057
	EBABC2	63.1705	63.1744	0.0039
P_{63}	BABC	52.1126	54.8725	1.5633
	EBABC1	48.0351	50.2229	1.6019
	EBABC2	48.4923	49.6881	0.8955
P_{73}	BABC	95.9524	103.0042	4.9146
	EBABC1	69.5606	74.3598	3.8114
	EBABC2	71.6904	78.8660	5.2703

[a] Scheduling problem
[b] Minimum
[c] Average
[d] Standard deviation

whether the population median of a dependent variable is the same across a given factor, while the Mann–Whitney test is generallly used to evaluate two different data populations, such as performance results from two separate algorithms (García et al. 2009; Lahoz-Beltra and Perales-Gravan 2010; Derrac et al. 2011).

- Kruskal–Wallis test for Table 12:
  - H_0: There is no performance difference between BABC, EBABC1 and EBABC2.
  - H_1: There is a performance difference between BABC, EBABC1 and EBABC2.
- Mann–Whitney test for Table 12:
  - H_0: There is no performance difference between two of three algorithms (BABC, EBABC1 and EBABC2).
  - H_1: There is a performance difference between two of three algorithms (BABC, EBABC1 and EBABC2).
- Kruskal–Wallis test for Table 13:
  - H_0: There is no performance difference between GA, SA, PSO and EBABC2.
  - H_1: There is a performance difference between GA, SA, PSO and EBABC2.
- Mann–Whitney test for Table 13:
  - H_0: There is no performance difference between two of four algorithms (GA, SA, PSO and EBABC2).
  - H_1: There is a performance difference between two of four algorithms (GA, SA, PSO and EBABC2).

The results of the non-parametric tests for a 95% significance level ($p < 0.05$) are shown in Table 12. These indicate that there are no statistically significant performance difference between BABC, EBABC1 and EBABC2 for the P_{11}, P_{21} and P_{41}. The difference in performance between BABC and EBABC2 is statistically significant for P_{31} and P_{51}, but the difference in performance between BABC and EBABC1 and between EBABC1 and EBABC2 are not significant for these problems. There are

Table 10 Performance comparison of BABC, EBABC1 and EBABC2 using P_{14}–P_{74}

P[a]	Algorithms	min[b]	$\bar{S}$[c]	σ[d]
P_{14}	BABC	66.2500	66.2500	0.0000
	EBABC1	66.2500	66.2833	0.0805
	EBABC2	66.2500	66.2500	0.0000
P_{24}	BABC	99.5365	99.5374	0.0006
	EBABC1	99.5363	99.5372	0.0006
	EBABC2	99.5362	99.5371	0.0006
P_{34}	BABC	38.5805	38.5965	0.0095
	EBABC1	38.5705	38.5766	0.0041
	EBABC2	38.5701	38.5792	0.0052
P_{44}	BABC	39.0014	39.0408	0.0372
	EBABC1	38.9816	39.0363	0.0415
	EBABC2	38.9832	39.0071	0.0151
P_{54}	BABC	70.1070	70.3677	0.5835
	EBABC1	70.0963	70.1059	0.0056
	EBABC2	70.1010	70.1065	0.0039
P_{64}	BABC	56.2268	59.1725	2.3682
	EBABC1	50.9021	53.1753	1.7575
	EBABC2	51.4135	53.1212	0.8952
P_{74}	BABC	96.0631	101.4588	3.0691
	EBABC1	69.0543	72.4296	3.0645
	EBABC2	70.7003	75.7897	3.8641

[a] Scheduling Problem

[b] Minimum

[c] Average

[d] Standard deviation

statistically significant differences in performance between BABC, EBABC1 and EBABC2 for problems P_{61} and P_{71}, but the difference between EBABC1 and EBABC2 is not significant. We have slightly different results for the P_{12}–P_{72}, P_{13}–P_{73}, P_{14}–P_{74} as shown in Table 12. The overall trend is differences become significant as job scheduling problems increase in sizes. We also do the statistical tests to compare the performance difference of our proposed EBABC2 with genetic algorithm (GA), simulated annealing (SA) and particle swarm optimization (PSO) proposed by Liu and et al. (2010) as shown in Table 13. PSO is better than GA and SA. There are statistically significant performance differences between EBABC2 and PSO. It means that our proposed EBABC2 is better than PSO.

In the ABC paradigm each bee finds a food source (solution) which represents a position in the problem space. Since the positions identified by each bee are in general different, the colony has the capability to explore the space searching for better solutions. The term *Diversity* is introduced to quantify the diversity of the colony and is defined as follows:

$$\text{Diversity} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\frac{1}{d}\sum_{j=1}^{d}(x_{ij}-\bar{x}_j)^2} \tag{29}$$

Here, n is the colony population size, d is the dimension of the search space (coordinates of the food sources), $\bar{x}$ is the centre point of the colony, and its j-th dimension is denoted by $\bar{x}_j$. Figure 10 shows the typical evolution of colony diversity for each of the three algorithms during an optimization run. In the EBABC1 algorithm the diversity undergoes a fluctuating decrease phase before stabilizing at a very low value after 300 generations. Two different phases can be observed with the EBABC2 algorithm. The diversity decreases, but stabilizes after 900 generations at a low state of diversity. In contrast, the BABC algorithm maintains colony diversity at its initial value throughout the optimization run. Considering Fig. 10, it can be seen that our algorithms initially provide large colony diversity facilitating exploration of the global solution space and then focuses on the current best solution with a refining step to achieve local exploitation. Experimental results

Table 11 Comparative study of EBABC2 with GA, SA and PSO using Liu et al. (2010) data (P_{11}–P_{71})

P[a]	GA		SA		PSO		EBABC2	
	$\bar{S}$[b]	σ[c]	$\bar{S}$[b]	σ[c]	$\bar{S}$[b]	σ[c]	$\bar{S}$[b]	σ[c]
P_{11}	47.1166	0.7700	46.6000	0.4855	46.2667	0.2855	46.0000	0.0000
P_{21}	85.7431	0.6218	90.7338	6.3834	84.0544	0.5030	85.5298	0.0006
P_{31}	42.9270	0.4151	55.4594	2.0605	41.9489	0.6944	41.5975	0.0028
P_{41}	38.0428	0.6613	41.7889	8.0772	37.6668	0.6068	35.1896	0.0089
P_{51}	63.1487	0.3726	70.5490	7.4141	62.0333	0.8810	59.1815	0.0041
P_{61}	55.5866	0.6068	65.4885	7.0464	54.7943	0.8517	52.9459	0.6648
P_{71}	73.1050	0.3690	83.7621	7.1029	72.9697	0.6057	71.0863	2.9236

[a] Scheduling problem

[b] Average

[c] Standard deviation

Table 12 Statistical analysis of the difference between BABC, EBABC1 and EBABC2 using the Kruskal–Wallis and Mann–Whitney tests

P^a	Kruskal–Wallis test	Mann–Whitney test		
		BABC, EBABC1	BABC,EBABC2	EBABC1, EBABC2
P_{11}	accept H_0			
P_{21}	accept H_0			
P_{31}	accept H_1	accept H_0	accept H_1	accept H_0
P_{41}	accept H_0			
P_{51}	accept H_1	accept H_0	accept H_1	accept H_0
P_{61}	accept H_1	accept H_1	accept H_1	accept H_0
P_{71}	accept H_1	accept H_1	accept H_1	accept H_0
P_{12}	accept H_0			
P_{22}	accept H_0			
P_{32}	accept H_1	accept H_0	accept H_1	accept H_0
P_{42}	accept H_0			
P_{52}	accept H_1	accept H_1	accept H_1	accept H_0
P_{62}	accept H_1	accept H_1	accept H_1	accept H_0
P_{72}	accept H_1	accept H_1	accept H_1	accept H_1
P_{13}	accept H_0			
P_{23}	accept H_0			
P_{33}	accept H_1	accept H_1	accept H_1	accept H_0
P_{43}	accept H_1	accept H_1	accept H_1	accept H_0
P_{53}	accept H_1	accept H_1	accept H_1	accept H_0
P_{63}	accept H_1	accept H_1	accept H_1	accept H_0
P_{73}	accept H_1	accept H_1	accept H_1	accept H_0
P_{14}	accept H_0			
P_{24}	accept H_0			
P_{34}	accept H_1	accept H_1	accept H_1	accept H_0
P_{44}	accept H_0			
P_{54}	accept H_1	accept H_1	accept H_1	accept H_0
P_{64}	accept H_1	accept H_1	accept H_1	accept H_0
P_{74}	accept H_1	accept H_1	accept H_1	accept H_1

[a] Scheduling problem

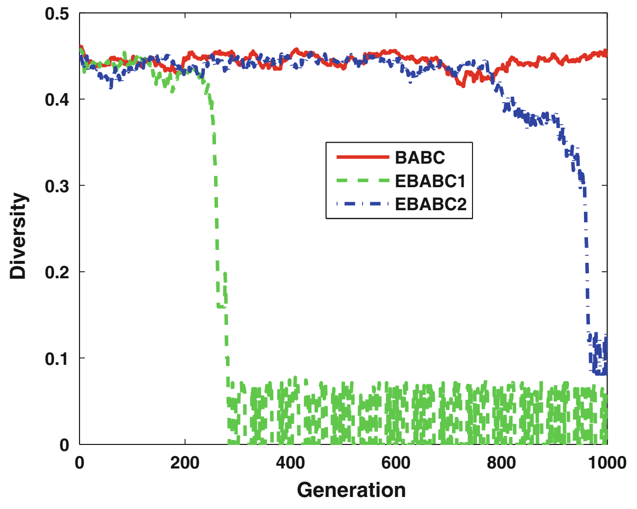


Fig. 10 Comparison of the evolution of colony diversity

illustrate that the algorithm achieves the best balance between global exploration and local exploitation.

6 Conclusions

The artificial bee colony (ABC) is relatively new and has the advantage of employing fewer control parameters compared with competing population-based algorithms. A binary implementation of ABC (BABC) is developed in this paper to solve the job scheduling problem for grid computing applications. We also develop EBABC, an extension of BABC that incorporates a flexible ranking strategy (FRS). Two variants of EBABC (namely, EBABC1 and EBABC2) are proposed that seek to achieve a balance between diversification and convergence of the search process, i.e. the exploration versus exploitation trade-off. Simulation results for a number of benchmark

Table 13 Statistical analysis of the difference between GA, SA, PSO and EBABC2 for P_{11}–P_{71} using the Kruskal–Wallis and Mann–Whitney tests

P^a	Kruskal–Wallis test	Mann–Whitney test					
		GA, SA	GA, PSO	GA,EBABC2	SA, PSO	SA, EBABC2	PSO, EBABC2
P_{11}	accept H_1	accept H_0	accept H_1	accept H_1	accept H_0	accept H_1	accept H_0
P_{21}	accept H_1	accept H_0	accept H_1	accept H_1	accept H_1	accept H_0	accept H_1
P_{31}	accept H_1	accept H_1	accept H_1	accept H_1	accept H_1	accept H_1	accept H_0
P_{41}	accept H_1	accept H_0	accept H_0	accept H_1	accept H_0	accept H_1	accept H_1
P_{51}	accept H_1	accept H_1	accept H_1	accept H_1	accept H_1	accept H_1	accept H_1
P_{61}	accept H_1	accept H_1	accept H_0	accept H_1	accept H_1	accept H_1	accept H_1
P_{71}	accept H_1	accept H_1	accept H_0	accept H_1	accept H_1	accept H_1	accept H_1

[a] Scheduling problem

job scheduling problems show that EBABC1 and EBABC2 outperform BABC for larger job scheduling problems and that in general they provide superior results to competing genetic algorithm, simulated annealing and particle swarm optimization based job scheduling algorithms.

An analysis of the dynamical diversity of the bee colonies further illustrates that the proposed algorithms, and in particular EBABC2, delivers a good balance between global exploration and local exploitation.

Acknowledgments The authors would like to thank Zhihua Cui for his scientific collaboration in this research work. This work is supported partly by the Kangwon National University, the National Natural Science Foundation of China (Grant No. 61173035, 61105117), the Fundamental Research Funds for the Central Universities (Grant No. 2012TD027), the Program for New Century Excellent Talents in University (Grant No. NCET-11-0861), and the Dalian Science and Technology Fund (Grant No. 2010J21DW006).

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