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A comprehensive survey: artificial bee colony (ABC) algorithm and applications

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Abstract Swarm intelligence (SI) is briefly defined as the collective behaviour of decentralized and self-organized swarms. The well known examples for these swarms are bird flocks, fish schools and the colony of social insects such as termites, ants and bees. In 1990s, especially two approaches based on ant colony and on fish schooling/bird flocking introduced have highly attracted the interest of researchers. Although the self-organization features are required by SI are strongly and clearly seen in honey bee colonies, unfortunately the researchers have recently started to be interested in the behaviour of these swarm systems to describe new intelligent approaches, especially from the beginning of 2000s. During a decade, several algorithms have been developed depending on different intelligent behaviours of honey bee swarms. Among those, artificial bee colony (ABC) is the one which has been most widely studied on and applied to solve the real world problems, so far. Day by day the number of researchers being interested in ABC algorithm increases rapidly. This work presents a comprehensive survey of the advances with ABC and its applications. It is hoped that this survey would be very beneficial for the researchers studying on SI, particularly ABC algorithm.

Keywords Swarm intelligence · Bee swarm intelligence · Artificial bee colony algorithm

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1 Introduction

Artificial Intelligence (AI) is one of the oldest and best known research fields. There are different definitions in the literature for AI of that the most widely used one belongs to John McCarthy, who defined it as “the science and engineering of making intelligent machines” (McCharty 2007). Computational intelligence (CI) is a fairly new research area and commonly referred to as AI, too. It is defined as the study of the design of intelligent agents where an intelligent agent is a system that perceives its environment and then takes actions to maximize its chances of success. While CI techniques are counted as AI techniques, there is a clear difference between them. For example, CI uses subsymbolic knowledge processing whereas classical AI uses symbolic approaches. CI includes a set of nature-inspired computational methodologies and approaches to address complex problems of the real world applications. Subjects in CI include neural networks which are trainable systems with very strong pattern recognition capabilities, fuzzy systems which are techniques for reasoning under uncertainty and evolutionary computation (EC) which is a form of stochastic optimization search. Forms of EC include swarm intelligence (SI) based algorithms and evolutionary algorithms. The evolutionary algorithms usually begin with a population of organisms (initial solutions) and then allow them to mutate and recombine, selecting only the fittest to survive each generation (refining solutions).The well-known evolutionary algorithms are genetic algorithms (GA), genetic programming, evolution strategies (ES), evolution programming and differential evolution (DE).

The term swarm is used for an aggregation of animals like fishes, birds and insects such as ants, termites and bees performing collective behaviour. The individual agents of these swarms behave without supervision and each of these agents has a stochastic behaviour due to her perception in the neighbourhood. SI is defined as the collective behaviour of decentralized and self-organized swarms. Well known examples of which are bird flocks and the colony of social insects such as ants and bees. The intelligence of the swarm lies in the networks of interactions among these simple agents, and between agents and the environment. SI is becoming increasingly important research area for computer scientists, engineers, economists, bioinformaticians, operational researchers, and many other disciplines. This is because the problems that the natural intelligent swarms can solve (finding food, dividing labour among nestmates, building nests etc.) have important counterparts in several engineering areas of real world. Two important approaches which are based on ant colony, called ant colony optimization (ACO), described by Dorigo et al. (1991) and based on bird flocking, called particle swarm optimization (PSO) introduced by Kennedy and Eberhart (1995) have proposed, in 1990s. Both approaches have been studied by many researchers and their several new versions have been described and applied to solve real-world problems in different areas. So many papers related with their applications have been presented to the literature and several survey papers regarding these studies have been prepared (Eberhart et al. 2001; Reyes-Sierra and Coello 2006; Blum 2005; Dorigo and Blum 2005).

The self-organization and division of labour features (Bonabeau et al. 1999) and the satisfaction principles (Millonas 1994) required by SI are strongly and clearly can be seen in honey bee colonies, the researchers have recently started to be interested in the behaviour of these swarm systems to propose new intelligent approaches, especially from the beginning of 2000s. The first comprehensive survey on the algorithms related to the bee SI and their applications was prepared by Karaboga and Akay (2009c). The survey shows that many algorithms have been developed by researchers depending on different intelligent behaviours of honey bee swarms in the last decade. The studies are mainly based on the dance and communication, task allocation, collective decision, nest site selection, mating, marriage, reproduction,

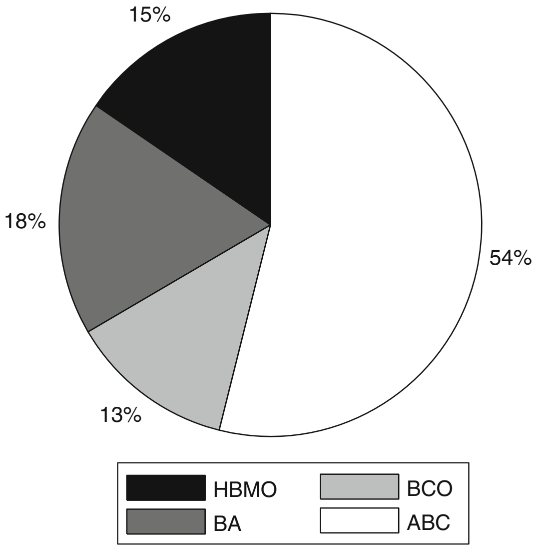

Fig. 1 Percentages of publications regarding to some algorithms based on bee swarms

foraging, floral and pheromone laying and navigation behaviours of the swarm. Some known algorithms based on bee SI are virtual bee, the bees, BeeAdHoc, the marriage in honeybees, the BeeHive, bee system, bee colony optimization and ABC.

Virtual bee algorithm was developed by Yang (2005) to solve the numerical function optimizations. In the model, a swarm of virtual bees are generated and they are allowed to move randomly in the phase space and these bees interact when they find some target nectar. Nectar sources correspond to the encoded values of the function. The solution for the optimization problem can be obtained from the intensity of bee interactions. The bees algorithm was described by Pham et al. (2005) and mimics the foraging behaviour of honey bees. In its basic version, the algorithm performs a kind of neighbourhood search combined with random search and can be used for both combinatorial optimization and functional optimization. BeeAdHoc algorithm, defined by Wedde and Farooq (2005), is a routing algorithm for energy efficient routing in mobile ad-hoc networks. The algorithm is inspired by the foraging principles of honey bees. The marriage in honeybees algorithm was presented by Abbass (2001). The model simulates the evolution of honey-bees starting with a solitary colony (single queen without a family) to the emergence of an eusocial colony (one or more queens with a family). BeeHive algorithm, which has been inspired by the communication in the hive of honey bees, was proposed by Wedde et al. (2004) and applied to the routing in networks. Bee system was introduced by Lucic and Teodorovic (2001) for solving difficult combinatorial optimization problems. Bee colony optimization was described by Teodorovic and Dell'orco (2005) for the ride-matching problem, for the routing and wavelength assignment in all-optical networks. ABC algorithm simulating foraging behaviour of honey bees was invented by Karaboga (2005). Among the algorithms mentioned above, ABC is the one which has been most widely studied and applied to solve the real-world problems, so far. The distribution of publications related to bee swarm intelligence with respect to the algorithms is presented in Fig. 1. As seen from the figure more than half (58%) of the publications belongs to ABC. However, to the best of our knowledge, there is no any survey paper in the literature reviewing the advances related to ABC algorithm and its applications. Therefore, the aim of this work is first to present the foraging behaviour of honey bees and the algorithmic implementation of ABC approach, and secondly to review the advances with ABC and its applications. Starting with a comprehensive introduction to the basic steps of the ABC algorithm, an extensive review of the modifications of ABC for tackling continuous, combinatorial, constrained, multiobjective, and large-scale optimization problems is presented and then an overview of various engineering applications of ABC is given. A number of future research directions is emphasized, as well. The content of the paper indicates the fact that ABC will continue to remain an active field of multi-disciplinary research within the next years. The survey was prepared by examining four different databases: Web of science, IEEE Explorer, ScienceDirect, SpringerLink. Additional to these databases Google web search engine is also used.

2 Artificial bee colony: ABC-approach

2.1 General features of intelligent swarms

There are so many kind of swarms in the world. It is not possible to call all of them intelligent or their intelligence level could be vary from swarm to swarm. Self-organization is a key feature of a swarm system which results collective behaviour by means of local interactions among simple agents (Bonabeau et al. 1999). Bonabeau et al. (1999) interpreted the self-organization in swarms through four characteristics:

(i) *Positive feedback*: promoting the creation of convenient structures. Recruitment and reinforcement such as trail laying and following in some ant species can be shown as example of positive feedback.
(ii) *Negative feedback*: counterbalancing positive feedback and helping to stabilize the collective pattern. In order to avoid the saturation which might occur in terms of available foragers a negative feedback mechanism is needed.
(iii) *Fluctuations*: random walks, errors, random task switching among swarm individuals which are vital for creativity. Randomness is often significant for emergent structures since it enables the discovery of new solutions.
(iv) *Multiple interactions*: agents in the swarm use the information coming from the other agents so that the information spreads throughout the network.

Additional to these characteristics, performing tasks simultaneously by specialized agents, called division of labour, is also an important feature of a swarm as well as self-organization for the occurrence of the intelligence (Bonabeau et al. 1997).

According to Millonas, in order to call a swarm intelligent, the swarm must satisfy the following principles (Millonas 1994):

(i) The swarm should be able to do simple space and time computations (the proximity principle).
(ii) The swarm should be able to respond to quality factors in the environment (the quality principle).
(iii) The swarm should not commit its activities along excessively narrow channels (the principle of diverse response).
(iv) The swarm should not change its mode of behaviour upon every fluctuation of the environment (the stability principle).
(v) The swarm must be able to change behaviour mode when needed (the adaptability principle).

2.2 Foraging behaviour of honey bees

The minimal model of forage selection that leads to the emergence of collective intelligence of honey bee swarms consists of three essential components: food sources, employed foragers and unemployed foragers, and the model defines two leading modes of the behaviour: the recruitment to a rich nectar source and the abandonment of a poor source.

(i) *Food Sources*: The value of a food source depends on many factors such as its proximity to the nest, its richness or concentration of its energy, and the ease of extracting this energy. For the sake of simplicity, the "profitability" of a food source can be represented with a single quantity (Seeley 1995).
(ii) *Employed foragers*: They are associated with a particular food source which they are currently exploiting or are "employed" at. They carry with them information about this particular source to the hive and the information can be the distance and direction from the nest, the profitability of the source and share this information with a certain probability.
(iii) *Unemployed foragers*: They are continually at look out for a food source to exploit. There are two types of unemployed foragers: scouts, searching the environment surrounding the nest for new food sources and onlookers waiting in the nest and establishing a food source through the information shared by employed foragers. The mean number of scouts averaged over conditions is about 5–10% of other bees (Seeley 1995).

The exchange of information among bees is the most important occurrence in the formation of the collective knowledge. While examining the entire hive it is possible to distinguish between some parts that commonly exist in all hives. The most important part of the hive with respect to exchanging information is the dancing area. Communication among bees related to the quality of food sources takes place in the dancing area. This dance is called a waggle dance. Since information about all the current rich sources is available to an onlooker on the dance floor, probably she watches numerous dances and decides to employ herself at the most profitable source. There is a greater probability of onlookers choosing more profitable sources since more information is circulated about the more profitable sources. Hence, the recruitment is proportional to the profitability of the food source (Tereshko and Loengarov 2005).

In the case of honey bees foraging behaviour, the four characteristics defined in the Sect. 2.1 on which self-organization relies can be expressed as follows:

(i) *Positive feedback*: As the nectar amount of a food source increases, the number of onlookers visiting it increases proportionally.
(ii) *Negative feedback*: The exploitation process of poor food sources is stopped by bees.
(iii) *Fluctuations*: The scouts carry out a random search process for discovering new food sources.
(iv) *Multiple interactions*: Employed bees share their information about food sources with their nest mates (onlookers) waiting on the dance area.

When the foraging behaviour of honey bees explained above is re-examined, it is seen that the principles defined by Millonas (1994) are fully satisfied.

2.3 Algorithmic structure of ABC

As in the minimal model of forage selection of real honey bees, the colony of artificial bees in ABC contains three groups of bees: *employed bees* associated with specific food sources, *onlooker bees* watching the dance of employed bees within the hive to choose a food source, and *scout bees* searching for food sources randomly. Both onlookers and scouts are also called unemployed bees. Initially, all food source positions are discovered by scout bees. Thereafter, the nectar of food sources are exploited by employed bees and onlooker bees, and this continual exploitation will ultimately cause them to become exhausted. Then, the employed bee which was exploiting the exhausted food source becomes a scout bee in search of further food sources once again. In other words, the employed bee whose food source has been exhausted becomes a scout bee. In ABC, the position of a food source represents a possible solution to the problem and the nectar amount of a food source corresponds to the quality (fitness) of the associated solution. In the basic form, the number of employed bees is equal to the number of food sources (solutions) since each employed bee is associated with one and only one food source.

The general algorithmic structure of the ABC optimization approach is given as follows:

Initialization Phase
REPEAT
    Employed Bees Phase
    Onlooker Bees Phase
    Scout Bees Phase
    Memorize the best solution achieved so far
UNTIL (Cycle = Maximum Cycle Number or a Maximum CPU time)

In the initialization phase, the population of food sources (solutions) is initialized by artificial scout bees and control parameters are set.

In the employed bees phase, artificial employed bees search for new food sources having more nectar within the neighbourhood of the food source in their memory. They find a neighbour food source and then evaluate its fitness. After producing the new food source, its fitness is calculated and a greedy selection is applied between it and its parent. After that, employed bees share their food source information with onlooker bees waiting in the hive by dancing on the dancing area.

In the onlooker bees phase, artificial onlooker bees probabilistically choose their food sources depending on the information provided by the employed bees. For this purpose, a fitness based selection technique can be used, such as the roulette wheel selection method.

After a food source for an onlooker bee is probabilistically chosen, a neighbourhood source is determined, and its fitness value is computed. As in the employed bees phase, a greedy selection is applied between two sources.

In the scout bees phase, employed bees whose solutions cannot be improved through a predetermined number of trials, called "limit", become scouts and their solutions are abandoned. Then, the scouts start to search for new solutions, randomly. Hence, those sources which are initially poor or have been made poor by exploitation are abandoned and negative feedback behaviour arises to balance the positive feedback.

These three steps are repeated until a termination criteria is satisfied, for example a maximum cycle number or a maximum CPU time.

3 Studies on ABC optimization

After the invention of ABC by Karaboga (2005), the fist conference paper introducing ABC was published in 2006 (Basturk and Karaboga 2006). The first journal article describing ABC and evaluating its performance was presented by Karaboga and Basturk (2007b), in which the performance of ABC was compared to GA, PSO and particle swarm inspired evolutionary algorithm. In 2008, the second article presenting a performance evaluation of ABC was published by Karaboga and Basturk (2008). In 2009, a public domain web-site (http://mf.erciyes.edu.tr/abc) dedicated to ABC was constructed. There are several source codes, written in different programming languages, of ABC and many publications about the modifications to ABC and their applications are presented in the website. The main algorithm of ABC is relatively simple and its implementation is, therefore, straightforward for solving optimization problems and ABC has been found to be very effective in the studies above, being able to produce very good results at a low computational cost. Therefore, after these initial publications many studies have been carried out on ABC. These studies can be grouped into three categories: comparisons and modifications, hybrid models and applications. In the following, the studies related to ABC are presented under these subtitles and discussions.

3.1 Comparisons and modifications

Originally, ABC optimization was proposed for solving numerical problems. Therefore, the first studies aimed to evaluate the performance of ABC on the widely used set of numerical benchmark test functions and to compare it with that of well-known evolutionary algorithms such as GA, PSO, DE and ACO. Karaboga and Basturk (2007b) compared the results of ABC with GA, PSO and particle swarm inspired evolutionary algorithm for optimizing multi-variable functions. Karaboga and Basturk (2008) compared the performance of ABC algorithm with DE, PSO and evolutionary algorithm (EA) for multi-dimensional numeric problems. Karaboga and Akay (2009b) presented a comparative study of ABC in which ABC is used for optimizing a large set of numerical test functions and its results were compared with GA, PSO, DE and ES. Mala et al. (2009) applied ABC for test suite optimization and compared it with ACO, and concluded that ABC based approach has several advantages over ACO. Krishnanand et al. (2009) presented a comparative study of five bio-inspired evolutionary optimization techniques including ABC. Karaboga and Akay (2009a) compared the performances of ABC with harmony search and bees algorithms on numerical optimization. Li et al. (2010c) compared the performance of the basic ABC, Bees and DE algorithms on eight well-known benchmark problems. Akay and Karaboga (2010) introduced modified versions of ABC algorithm and applied them for efficiently solving real-parameter optimization problems. Chu et al. (2011) presented an overview of algorithms for SI, which includes ABC. Ruiz-Vanoye and Daz-Parra (2011) studied the functional similarities between meta-heuristic algorithms including ABC and the science of life. Dongli et al. (2011) proposed a modified ABC algorithm for numerical optimization problems and tested its performance on a set of benchmark problems. Wu et al. (2011d) described an improved ABC algorithm to enhance the global search ability of basic ABC. Rajasekhar et al. (2011b) proposed an improved version of ABC algorithm with mutation based on Levy probability distributions. Mohammed and El-Abd (2012) carried out a performance assessment study of foraging, including ABC, and evolutionary algorithms.

The success of the ABC algorithm as a single-objective optimizer (mainly when dealing with continuous search spaces) has motivated researchers to extend the use of this algorithm to other areas. For example, Akay and Karaboga (2009b) applied ABC to integer programming problems and concluded that ABC can handle integer programming problems efficiently. Wang et al. (2010b) proposed ABC to determine free parameters of support vector machine and the binary ABC to obtain the optimum feature selection for intrusion detection systems. Kashan et al. (2011) introduced a new version of ABC, called DisABC, which is particularly designed for binary optimization, in which DisABC uses a new differential expression which employs a measure of dissimilarity between binary vectors in place of the vector subtraction operator typically used in the original ABC algorithm. Karaboga and Gorkemli (2011) introduced a combinatorial ABC for travelling salesman problems. Li et al. (2011e) proposed an ABC for travelling salesman problem by combining the modified nearest neighbour approach and the improved inver-over operation.

Some researchers have investigated the effect of control parameters and the strategies employed in ABC on its performance and then proposed new strategies. Akay and Karaboga (2009a) studied on the parameter tuning of the ABC algorithm and investigated the effect of control parameters. Bao and Zeng (2009) studied on comparison and analysis of the selection mechanisms in the ABC and they considered several selection strategies, such as disruptive selection strategy, tournament selection strategy and rank selection strategy. Ho and Yang (2009) described an ABC algorithm for inverse electromagnetic problem, in which for intensification searches, some novel formulas are proposed for the employed bees and onlookers to carry out exploiting searches around specific memorized food sources. Aderhold et al. (2010) studied on the influence of the population size on the optimization behaviour of ABC and also proposed two variants of ABC which use the new methods for the position update of the artificial bees. Pansuwan et al. (2010) studied on identifying optimum ABC algorithm's parameters for scheduling the manufacture and assembly of complex products. Guo et al. (2011) presented a novel search strategy for the main three procedures and the improved algorithm is called global ABC which has great advantages of convergence property and solution quality. Alam et al. (2010) introduced a novel adaptation scheme of mutation step size for ABC and compared its results with a number of SI and population based optimization algorithms on complex multi-modal benchmark problems. Mohan and Baskaran (2011) have restructured ABC algorithm from the initialization phase to the implementation phase and described an energy aware and energy efficient routing protocol for adhoc network by using restructured ABC. Lee and Cai (2011) proposed a new diversity strategy improved ABC algorithm. Diwold et al. (2011) proposed two new variants of ABC which use new methods for the position update of the artificial bees. Stanarevic (2011) studied on the comparison of different mutation strategies applied to ABC algorithm. Rajasekhar et al. (2011b) proposed an improved version of ABC algorithm with mutation based on Levy probability distributions. Zou et al. (2011) proposed a new variant of the ABC algorithm based on Von Neumann topology structure, namely Von Neumann neighbourhood ABC.

The original ABC was proposed for solving unconstrained optimization problems and later on it was extended to constrained problems. Karaboga and Basturk (2007a) extended ABC algorithm for solving constrained optimization problems and applied it to a set of constrained problems. Brajevic et al. (2010) presented an improved version of ABC for constrained optimization problems, which has been implemented and tested on several engineering benchmarks which contain discrete and continuous variables. Mezura-Montes et al. (2010) presented a novel ABC algorithm to solve constrained numerical optimization problems. Mezura-Montes and Velez-Koeppel (2010) introduced a novel algorithm based on the ABC to solve constrained real-parameter optimization problems, in which a dynamic tolerance control mechanism for equality constraints was added to the algorithm in order to facilitate the approach to the feasible region of the search space. Stanarevic et al. (2010) presented a modified ABC algorithm for constrained problems which employs a "smart bee" having memory to keep the location and quality of food sources. Karaboga and Akay (2011) described a modified ABC algorithm for constrained optimization problems and compared its performance against those of state-of-the-art algorithms for a set of constrained test problems. Brajevic et al. (2011) studied on an improved version of the ABC algorithm adjusted for constrained optimization problems.Akay and Karaboga (2012) described an ABC algorithm for large-scale problems and engineering design optimization.

As the problem scale grows, increasing the number of colony size will improve the chance of finding a good solution. Therefore, several researchers attempted to implement ABC in parallel. Tsai et al. (2009) introduced an enhanced ABC algorithm, which is called the interactive ABC, for numerical problems. Narasimhan (2009) presented a parallel version of the ABC for shared memory architectures and showed that the proposed parallelization strategy does not degrade the quality of solutions obtained, but achieves substantial speed-up. Subotic et al. (2010) introduced the parallelization of ABC and different threads were assigned to separate swarms and different types of communications among these swarms were described and examined. Zou et al. (2010b) presented an extended version of ABC algorithm, namely, the cooperative ABC and used it for optimizing widely employed benchmark functions. El-Abd (2010) proposed a cooperative approach to the ABC algorithm based and applied to a well-known set of classical benchmark functions. Vargas Bentez and Lopes (2010) introduced a parallel ABC approach for protein structure prediction by using the 3DHP-SC model. Parpinelli et al. (2010) investigated the parallelization of ABC and they compared three parallel models: master-slave, multi-hive with migrations, and hybrid hierarchical. Luo et al. (2010) described a communication strategy for the parallelized ABC for solving numerical optimization problems, in which the proposed communication strategy provides the information flow for the agents to communicate in different sub-populations. Banharnsakun et al. (2010b) introduced a parallel ABC algorithm in which the entire bee colony is decomposed into several subgroups and then each subgroup performs a local search concurrently on each processor node. The local best solutions are then exchanged among processor nodes. Zou et al. (2010a) presented a cooperative ABC which significantly improves the original ABC in solving complex optimization problems. Subotic et al. (2011) studied on approaches in parallelization of the ABC algorithm.

Concepts related to evolutionary optimization algorithms have been integrated with ABC to improve its performance. Liu and Cai (2009) proposed a variation on the traditional ABC algorithm, called the artificial bee colony programming, employing randomized distribution, bit hyper-mutation and a novel crossover operator to improve the performance of the original algorithm. Inspired by PSO, Zhu and Kwong (2010) proposed an improved ABC algorithm called gbest-guided ABC by incorporating the information of global best solution into the solution search equation. Xu and Lei (2010) applied an improved version of ABC named ABC_SA, which is presented to prevent the algorithm from sliding into local optimum by introducing Metropolis acceptance criteria into ABC's searching process, to solve multiple sequence alignment problem. Lei et al. (2010a) proposed some modification on the original iteration equation of ABC, in which an inertial weight is added on the first item to balance the local and the global search, inspired by the improved strategies of PSO and applied the improved ABC to data clustering problem. Banharnsakun et al. (2011a) introduced the best-so-far selection in ABC and assessed its performance on two sets of problems: numerical benchmark functions and image registration applications. An improved ABC algorithm by the inspiration of DE algorithm was proposed by Gao and Liu (2011) and they demonstrated its good performance in solving complex numerical optimization problems. Rajasekhar et al. (2011a) proposed a modified version of ABC known as Cauchy mutation ABC for tuning PI controller for speed regulation in permanent magnet synchronous motors drive. Raziuddin et al. (2011) introduced the differential ABC to enhance the bees update strategy for improving the quality of solutions. Tuba et al. (2011) presented a novel algorithm named GABC which integrates ABC algorithm with self-adaptive guidance adjusted for engineering optimization problems. Li et al. (2011a) proposed an improved ABC algorithm in which inertia weight and acceleration coefficients are introduced to improve the search process of ABC algorithm. Banharnsakun et al. (2011) proposed an effective scheduling method based on best-so-far ABC for solving the JSSP, in which the solution direction is biased toward the best-so-far solution rather a neighbouring solution as proposed in the original ABC method. Bi and Wang (2011) presented an improved ABC called fast mutation ABC in which a mutation strategy based on opposition-based learning is employed instead of the behaviour of scouts. Inspired by DE, Gao and Liu (2012) proposed an improved solution search equation for ABC, which is based on that the bee searches only around the best solution of the previous iteration to improve the exploitation process.

Some researchers proposed to import chaotic theory concepts to ABC. Lin et al. (2009) presented an ABC based on chaotic sequences and psychology factor of emotion and called this algorithm emotional chaotic ABC. Xu et al. (2010) described a chaotic ABC approach and applied this algorithm for path planning of uninhabited combat air vehicle in various combat field environments. Alatas (2010) aimed a new ABC algorithm using chaotic maps for parameter adaptation in order to improve the convergence characteristics and to prevent the ABC to get stuck on local solutions. Zhang et al. (2011e) introduced an ABC with chaotic theory to solve the partitional clustering problem and after investigating the optimization model including both the encoding strategy and the variance ratio criterion, they developed a chaotic ABC algorithm based on the Rossler attractor. Zhang et al. (2011c) described an improved ABC based on both fitness scaling and chaotic theory, therefore called scaled chaotic ABC, and used this algorithm to train a feed-forward neural network for the problem of magnetic resonance brain image classification. Ayan and Kilic (2011) proposed a chaotic ABC algorithm and applied this algorithm to the multi objective optimum power flow problem. Hong (2011) presented an electric load forecasting model which combines the seasonal recurrent support vector regression model with chaotic ABC algorithm to improve the forecasting performance. In order to improve the convergence characteristics and to prevent the ABC to get stuck in local solutions, Wu and Fan (2011) proposed a chaotic ABC that uses chaotic searching behaviour for candidate food position production. Zhang et al. (2011d) introduced a fitness-scaling chaotic ABC approach as a fast and robust approach for the task of path planning of UCAV. Yan and Li (2011) described an effective refinement ABC optimization algorithm based on chaotic search and applied for PID control tuning.

Optimization problems which have more than one objective function are quite common in many areas. This type problems are called multi-objective and several authors applied ABC for solving these problems. Hedayatzadeh et al. (2010) adapted the original ABC to multi-objective problems with a grid based approach for maintaining and adaptively assessing the Pareto front. Omkar et al. (2011b) presented a generic method/model for multi-objective design optimization of laminated composite components, based on vector evaluated ABC algorithm. Akbari et al. (2011) introduced a multi-objective ABC optimization method for optimizing problems with multiple objectives. Rubio-Largo et al. (2011) applied a multi-objective ABC to the static routing and wavelength assignment problem. Gonzlez-lvarez et al. (2011) proposed the application of a multi-objective ABC to solve the motif discovery problem and applied it to the specific task of discovering novel transcription factor binding sites in DNA sequences. Atashkari et al. (2011) introduced a multi-objective ABC for optimization of power and heating system. Arsuaga-Rios et al. (2011) presented a multi-objective ABC for scheduling experiments across the grid and the well-known deadline budget constraint algorithm from Nimrod-G and the workload management system scheduler from the middle-ware gLite (lightweight middle ware for grid computing) were compared with the proposed algorithm. Zhang et al. (2011a) described a hybrid multi-objective ABC for burdening optimization of copper strip production. Omkar et al. (2011a) introduced vector evaluated and objective switching approaches of ABC Algorithm for multi-objective design optimization of composite plate structures. Zou et al. (2012) presented a novel algorithm based on ABC, which uses the concept of Pareto dominance to determine the flight direction of a bee, to deal with multi-objective optimization problems.

Other modifications to ABC to improve its performance are: Quan and Shi (2008) introduced an improved ABC in which a new search iteration operator based on the fixed point theorem of contractive mapping in banach spaces is proposed. dos Santos Coelho and Alotto (2010) proposed a Gaussian ABC approach and applied it to Loney's solenoid benchmark problem. Shi et al. (2010b) described an ABC with random key for resource-constrained project scheduling in real time. de Oliveira and Schirru (2011) presented an ABC with random keys and used for optimizing the ICFMO problem of a Brazilian "2-loop" pressurized water reactor nuclear power plant and the results obtained with the proposed algorithm were compared with GA and PSO. dos Santos Coelho and Alotto (2011) introduced the Gaussian ABC algorithm and applied the standard and the improved version to Loney's solenoid problem, showing the suitability of these methods for electromagnetic optimization. Kang et al. (2011a) described a Rosenbrock ABC that combines Rosenbrock's rotational direction method with ABC for accurate numerical optimization. Monica et al. (2011) proposed a modified ABC based on low discrepancy Sobol sequence called Sobol sequence guided ABC. Wei et al. (2011) introduced a novel ABC algorithm based on attraction pheromone for the multidimensional knapsack problems.

3.2 Hybridization

In order to make ABC more powerful, it was combined with some traditional and evolutionary optimization algorithms. This type ABC is called hybridized ABC. A hybrid simplex ABC algorithm which combines Nelder-Mead simplex method with ABC was introduced and used to improve the search efficiency in computation by Kang et al. (2009a) and used for inverse analysis problems by Kang et al. (2009b). Marinakis et al. (2009) presented a new hybrid algorithm, which is based on the concepts of ABC and greedy randomized adaptive search procedure, for optimally clustering n objects into k clusters. Duan et al. (2009) introduced a hybrid quantum evolutionary algorithm with ABC optimization. Pulikanti and Singh (2009) proposed a new hybrid approach combining ABC algorithm with a greedy heuristic and a local search for the quadratic knapsack problem. Borovska and Yanchev (2009) described a parallel metaheuristic algorithm based on EC, ABC and ACO and trajectory based methods (GRASP, TS and simulated annealing (SA)) for solving the timetabling and the job shop scheduling problems. Duan et al. (2010) introduced a novel hybrid ABC and quantum evolutionary algorithm for solving continuous optimization problems. Shi et al. (2010a) proposed a novel hybrid swarm intelligent algorithm based on PSO and ABC. Kang et al. (2010) presented a novel hybrid Hooke Jeeves ABC algorithm with intensification search based on the Hooke Jeeves pattern search and ABC. Banharnsakun et al. (2010a) introduced a hybrid method for solving the travelling salesman problem in which the exploitation process in ABC algorithm is improved upon by the greedy subtour crossover method. Gao and Han (2010) described a method for direction finding of signal subspace fitting by cultural bee colony algorithm. Jatoth and Rajasekhar (2010) proposed a novel hybrid approach involving GA and ABC to enhance the efficiency of ABC and used this algorithm for tuning PI speed controller in a vector-controlled permanent magnet synchronous motor drive. Zhao et al. (2010b) described a novel hybrid swarm intelligent approach which is based on the idea of the parallel computation merit of GA, and the speed and self-improvement merits of ABC. Tsai et al. (2010) proposed a new framework for optimization based-on hybrid SI in which cat swarm optimization and ABC are combined. Li and Chan (2011) described a hybrid learning method combining ABC and the recursive least square estimator algorithm for training the proposed complex neural fuzzy system. El-Abd (2011) investigated hybridization of ABC with PSO where the PSO algorithm is augmented with ABC component to improve the personal bests of the particles. Schiffmann and Sebastiani (2011) presented an algorithmic extension of a numerical optimization scheme, a variant of the ABC algorithm which couples deterministic (downhill gradient) and stochastic elements to avoid local minimum trapping, for analytic capping potentials for use in mixed quantum-classical (quantum mechanical/molecular mechanical, QM/MM) ab initio calculations. Li et al. (2011d) proposed an effective ABC for solving the flexible job shop scheduling problems, in which a tabu search (TS) is integrated to perform local search for employed bee, onlookers, and scout bees. Alzaqebah and Abdullah (2011c) introduced a hybrid ABC based on disruptive selection process for examination timetabling problems. Ozturk and Karaboga (2011) introduced a hybrid algorithm combining ABC with Levenberq-Marquardt algorithm to train artificial neural networks. Zhang et al. (2011b) presented a novel hybrid ABC to solve the travelling salesman problem in which the aim is to hybridize the solution construction mechanism of ABC with path relinking, an evolutionary method, which introduce progressively attributes of the guiding solution into the initial solution to obtain the high quality solution as quickly as possible. In order to improve the intensification ability of ABC, Zhong et al. (2011) proposed a hybrid ABC algorithm where chemotaxis behaviour of bacterial foraging optimization algorithm is embedded into the exploitation process of employed bees and onlooker bees. Oner et al. (2011) described a hybrid algorithm composed of a heuristic graph node colouring algorithm and ABC to solve course scheduling problem. Yeh et al. (2011) presented a study which combines a bee recurrent neural network optimized by the ABC algorithm with Monte Carlo simulation to generate a novel approximate model for predicting network reliability. Xiao and Chen (2011) introduced a hybrid ABC with artificial immune network algorithm and used this algorithm to solve multi-mode resource constrained multi-project scheduling problem. Bin and Qian (2011) described a differential ABC algorithm for global numerical optimization. Sharma and Pant (2011) suggested the incorporation of DE operators in the structure of basic ABC algorithm. Kang et al. (2011b) presented a novel hybrid Hooke Jeeves ABC algorithm with intensification search based on the Hooke Jeeves pattern search and the ABC and demonstrated how the standard ABC can be improved by incorporating a hybridization strategy. Li and Jian-chao (2011) aimed a novel bi-group differential ABC algorithm which is combined with (DE) to improve the performance of ABC. Rajasekhar et al. (2011c) studied on a novel hybrid differential ABC algorithm, which combines DE with ABC algorithm, for designing the fractional order PI controller in a surface-mounted permanent magnet synchronous motor drive. Sundar and Singh (2012) presented a hybrid approach combining ABC with a local search to solve the non-unicost set covering problem.

3.3 Applications

ABC has been used in many applications in several different fields. One of the most interesting application area is training neural networks. Karaboga et al. (2007) employed ABC for training feed-forward neural networks, i.e. searching optimal weight set. Karaboga and Akay (2007) tested ABC on training on artificial neural networks which are widely used in signal processing applications. Karaboga and Ozturk (2009) applied ABC on training feed-forward neural networks to classify different data sets which are widely used in the machine learning community. Omkar and Senthilnath (2009) employed ABC to train a multilayer perceptron neural network which is used for the classification of the acoustic emission signal to their respective source. Kurban and Besdok (2009) studied on a comparison of RBF neural network training algorithms for inertial sensor based terrain classification. Irani and Nasimi (2011) used ABC to train neural network for bottom hole pressure prediction in underbalanced drilling. Ozkan et al. (2011) applied ABC for training neural networks for modelling daily reference evapotranspiration (ET0) modelling. Parmaksizoglu and Alci (2011) used ABC to design the cloning template of goal-oriented C cellular neural networks architecture. Garro et al. (2011) presented an ABC based synthesis methodology for neural networks, that maximizes its accuracy and minimizes the number of connections of an artificial neural network by evolving the weights, the architecture and the transfer functions of each neuron. Hsieh et al. (2011) introduced an integrated system where wavelet transforms and recurrent neural network based on ABC (called ABC-RNN) are combined for stock price forecasting. Kumbhar and Krishnan (2011) described an ABC based methodology, which maximizes its accuracy and minimizes the number of connections of an artificial neural network by evolving at the same time the synaptic weights, the artificial neural network's architecture and the transfer functions of each neuron. Shah et al. (2011) used ABC algorithm to train MLP and showed that MLP-ABC performance is better than MLP-BP for time series data. Yeh and Hsieh (2012) described ABC based neural networks for S-system models of biochemical networks approximation.

ABC was used by some researchers to solve the optimization problems encountered in electrical engineering. Rao et al. (2008) presented a new method which applies an ABC algorithm for determining the sectionalizing switch to be operated in order to solve the distribution system loss minimization problem. de Oliveira et al. (2009) studied on the performance of an ABC optimization algorithm applied to the accident diagnosis in a pwr nuclear power plant. Lalitha et al. (2010) applied ABC algorithm for DG placement for minimum loss in radial distribution system. Rao (2010) presented a new method based on ABC for capacitor placement in distribution systems with an objective of improving the voltage profile and reduction of power loss. Yousefi-Talouki et al. (2010) proposed a solution of optimal power flow incorporating unified power flow controller, as a powerful and versatile FACTS devices, using ABC. Abu-Mouti and El-Hawary (2010) described a priority-ordered constrained search technique for optimal distributed generation allocation in radial distribution feeder systems which is based on ABC. Ozturk et al. (2010) applied ABC to reactive power optimization problem and tested its performance on ten bus system and the results were compared with the improving strength Pareto EA. Cobanli et al. (2010) introduced a method based on ABC for active power loss minimization in electric power systems. Chatterjee et al. (2010) employed ABC for optimizing the different tunable parameters of the hybrid power system model. Abachizadeh et al. (2010b) used ABC for the optimization of a beam-type IPMC actuator. Sumpavakup et al. (2010) described the use of ABC to solve the optimal power flow problems. Linh and Anh (2010) presented ABC for determining the sectionalizing switch to be operated in order to solve the distribution system loss minimization problem. Doğan and Alçı (2011) used ABC to provide optimal power flow without exceeding power system operating conditions in IEEE-30 bus test system. Ayan and Kılıç (2011b) solved optimal reactive power flow which is a non-linear complex optimization problem in energy transmission lines by ABC algorithm based on chaos theory. Özyön et al. (2011a) converted the environmental economic power dispatch problem which is a multi-objective optimization problem into a single objective optimization problem using the weighted sum method and solve this converted problem by ABC algorithm. Ayan and Kılıç (2011a) employed ABC to solve optimal power flow problem and applied it to IEEE-11 bus test system. Özyön et al. (2011b) used ABC algorithm for the solution of the economic dispatch problem with valve point effect where fuel cost curve increases as sinusoidal oscillations. Bijami et al. (2011) employed an artificial bee colony algorithm for simultaneous coordinated tuning of two power system stabilizers to damp the power system inter-area oscillations. Shayeghi et al. (2011) presented an ABC algorithm for optimal tuning of the power system stabilizer in a single-machine infinite-bus power system. Dutta et al. (2011) applied ABC for optimal control of flexible smart structures bonded with piezoelectric actuators and sensor and the optimal locations of actuators/sensors and feedback gain are obtained by maximizing the energy dissipated by the feedback control system. Eke et al. (2011) described the optimal tuning for the parameters of the power system stabilizer, which can improve the system damping performance within a wide region of operation conditions to enhance power system stability using ABC. Ravi and Duraiswamy (2011) exploited the use of ABC algorithm for better stability of the power system. Baijal et al. (2011) applied ABC to solve the economic load dispatch problem. Sarma and Rafi (2011) presented a new method which applies ABC for capacitor placement in distribution systems with an objective of improving the voltage profile and reduction of power loss. Gozde and Taplamacioglu (2011) presented a study on comparative performance analysis of ABC for automatic voltage regulator (AVR) system and they showed that the ABC algorithm can be successfully applied to the AVR system for improving the performance of the controller.

ABC has found several applications in mechanical and civil engineering areas. Rao and Pawar (2009) employed ABC for modelling and optimization of process parameters of wire electrical discharge machining. Rao and Pawar (2010b) used ABC for the parameter optimization of a multi-pass milling process and compared its results with PSO and SA. Gomez-Iglesias et al. (2010) described a modification on the original ABC algorithm to optimise the equilibrium of confined plasma in a nuclear fusion device and its adaption to a grid computing environment. Yao et al. (2010) presented a method based on ABC to locate the subway routes which aims to maximize the population covered by subway routes. Hadidi et al. (2010) introduced an ABC algorithm for structural optimization of planar and space trusses under stress, displacement and buckling constraints. Hetmaniok et al. (2010) presented a numerical method of solving the inverse heat conduction problem based on ABC algorithm. Rao et al. (2010a) employed ABC for the parameter optimization of ultrasonic machining process. Rao and Pawar (2010a) applied ABC to grinding process parameter optimization and compared the results with the previously published results obtained by using other optimization techniques. Rao and Patel (2011b) described the optimization of mechanical draft counter flow wet-cooling tower using ABC algorithm. Şahin et al. (2011) used ABC for the design and economic optimization of shell and tube heat exchangers. Rashidi et al. (2011) studied on the parametric analysis and optimization of regenerative Clausius and organic Rankine cycles with two feedwater heaters using ABC. Zielonka et al. (2011) proposed ABC for minimizing the proper functional, which allows to reconstruct the value of heat transfer coefficient in the successive cooling zones. Mandal et al. (2011) studied on the leak detection of pipelines and described an integrated approach of rough set theory and ABC trained SVM. Sonmez (2011b) described the modifications on the basic ABC in order to solve discrete optimization problems and applied the proposed algorithm to the design of truss structures. Sonmez (2011a) applied ABC with an adaptive penalty function approach (ABC-AP) to minimize the weight of truss structures. Rao and Patel (2011a) explored the use of ABC algorithm for the design optimization of rotary regenerator. Samanta and Chakraborty (2011) applied ABC to search out the optimal combinations of different operating parameters for three widely used non-traditional machining processes, i.e. electrochemical machining, electrochemical discharge machining and electrochemical micromachining processes.

An interesting application area of ABC is data mining. Particularly clustering, feature selection and rule discovery. Karaboga and Ozturk (2011) proposed a novel clustering approach based on ABC and tested it on thirteen of typical test data sets from the UCI Machine Learning Repository. Zhang et al. (2010) presented an ABC clustering algorithm to optimally partition n objects into k clusters where Deb's rules are used to direct the search direction of each candidate. Karaboga and Ozturk (2010) tested the performance of ABC on fuzzy clustering and showed that ABC algorithm is also successful in fuzzy clustering. Karaboga et al. (2010) proposed a novel hierarchical clustering approach for wireless sensor networks to maintain energy depletion of the network in minimum by using ABC. Wu et al. (2011b) introduced a new method using ABC for clustering the protein-protein interaction network based on the functional flow model. Celik et al. (2011) described a new and novel heuristic classification data mining approach based on ABC called ABC data miner. Hsieh and Yeh (2011) proposed a concept for machine learning that integrates a grid scheme into a least squares support vector machine (called GS-LSSVM) for classification problems, where ABC is used to optimize parameters for LSSVM learning. Zhang et al. (2011f) described a methodology for automatically extracting a convenient version of T-S fuzzy models from data using a novel clustering technique, called variable string length ABC algorithm based fuzzy c-means clustering approach. Li et al. (2011c) studied on study the risk of dams in the perspective of clustering analysis and to improve the performance of fuzzy c-means clustering they proposed an ABC with fuzzy c-means. Zhao and Zhang (2011) proposed an improved kernel fuzzy c-means clustering algorithm based on ABC which integrates the advantages of kernel fuzzy c-means and ABC algorithm. Babu et al. (2011) created both sheep and goat disease database by using rule-based techniques and ABC algorithm. Selvakumar and Nazer (2011) studied on the design of garlic expert systems using ABC algorithm to advice the farmers in villages through online. Abedinia et al. (2011) presented an ABC algorithm to tune optimal rule-base of a fuzzy power system stabilizer which leads to damp low frequency oscillation following disturbances in power systems. Babu and Rao (2010a) developed a new "Garlic Expert Advisory System" based on ABC, which aims to identify the diseases and disease management in garlic crop production to advise the farmers in the villages to obtain standardized yields. Suguna and Thanushkodi (2011) introduced an improved rough set-based attribute reduction (RSAR) namely independent RSAR hybrid with ABC algorithm, which finds the subset of attributes independently based on decision attributes (classes) at first and then finds the final reduct. Shukran et al. (2011) proposed the use of the ABC algorithm as a new tool for data mining particularly in classification tasks and indicated that ABC algorithm is competitive, not only with other evolutionary techniques, but also to industry standard algorithms such as PART, SOM, naive bayes, classification tree and nearest neighbour (kNN). Shokouhifar and Sabet (2010) described a hybrid approach for effective feature selection using neural networks and ABC optimization. Sridhar et al. (2010) studied on the implementation of web-based chilli expert advisory system using ABC optimization. Babu and Rao (2010b) described an implementation of parallel optimized ABC algorithm with SMA technique for garlic expert advisory system.

A few applications of ABC are related to wireless sensor networks. Udgata et al. (2009) studied on the use of ABC for the sensor deployment problem which is modelled as a data clustering problem. Mini et al. (2010) applied ABC to the problem of sensor deployment in 3-D terrain. Ozturk et al. (2011) described ABC based a dynamic deployment approach for stationary and mobile sensor networks to achieve better performance by trying to increase the coverage area of the network. Mini et al. (2011) introduced ABC based sensor deployment algorithm for target coverage problem in 3-D terrain. Okdem et al. (2011) evaluated the performance of ABC on routing operations in wireless sensor networks. Öztürk et al. (2012) applied ABC to the dynamic deployment of mobile sensor networks to gain better performance by trying to increase the coverage area of the network.

ABC have been employed to solve several problems in image processing area. Benala et al. (2009) proposed a novel approach to image edge enhancement using ABC for hybridized smoothening filters. Chidambaram and Lopes (2009) applied ABC to the object recognition in the images to find a pattern or reference image (template) of an object. Nebti and Boukerram (2010) employed ABC for the problem of handwritten digits recognition where it has been used as classifier. Zhang and Wu (2011) proposed a global multi-level thresholding method for image segmentation which is based on ABC approach. Xu and Duan (2010) described a novel shape-matching approach to visual target recognition for aircraft at low altitude where ABC is employed to optimize edge potential function. Ma et al. (2011) proposed a fast synthetic aperture radar image segmentation method based on ABC algorithm which is introduced to search for the optimal threshold. Zhiwei et al. (2011) introduced a new method based on ABC algorithm to select image threshold automatically. Akay and Karaboga (2011) presented a study in which ABC was used to determine the thresholds to produce the best compressed image in terms of both compression ratio and quality. Taherdangkoo et al. (2010) described a method for segmentation of MR brain images using the fuzzy C-mean algorithm improved by ABC algorithm. Zhao et al. (2010a) applied an ABC algorithm for direction finding of maximum likelihood algorithm and proved that the proposed method has some good performance such as high resolution in the presence of impulse noise. Horng and Jiang (2010) introduced a new multilevel maximum entropy thresholding algorithm based on the technology of ABC method for image processing and pattern recognition problems. Horng (2011) proposed a new multilevel maximum entropy thresholding algorithm based on the technology of ABC and the experimental results demonstrated that the proposed algorithm can search for multiple thresholds which are very close to the optimum ones examined by the exhaustive search method. Cuevas et al. (2012) presented an approach based on ABC for automatic detection of multiple circular shapes on images that considers the overall process as a multi-modal optimization problem. Çivicioğlu (2011) applied ABC for solving image segmentation problem. Shokouhifar and Abkenar (2011) described an ABC for MRI fuzzy segmentation of brain tissue. Chidambaram and Lopes (2010) proposed an improved ABC algorithm for the object recognition problem in complex digital images using template matching. Wang (2011) developed a novel image registration technique based on ABC. Ye et al. (2011) introduced a method for image enhancement based on ABC algorithm and fuzzy set. Zhang and Wu (2011b) focused on the problem of human face pose estimation using single image and introduced a face pose estimation method based on ABC.

Although the original ABC was firstly described for solving numerical problems, the extended versions have been introduced for the discrete and combinatorial type problems. Szeto et al. (2011) proposed an enhanced version of ABC to improve the solution quality of the original version and used it for solving the capacitated vehicle routing problem. Yeh and Hsieh (2011) developed a penalty guided ABC algorithm to solve the reliability redundancy allocation problem. Tasgetiren et al. (2011b) presented a discrete ABC algorithm hybridized with a variant of iterated greedy algorithms to find the permutation that gives the smallest total flowtime. Li et al. (2011e) described a Pareto-based discrete ABC algorithm for multi-objective flexible job shop scheduling problems. Pan et al. (2011) proposed a discrete ABC to solve the lot-streaming flow shop scheduling problem with the criterion of total weighted earliness and tardiness penalties under both the idling and no-idling cases. Ziarati et al. (2011) investigated the application of ABC for resource constrained project scheduling problem. Li et al. (2011f) developed a hybrid ABC algorithm for flexible job shop scheduling problems and experimental showed the efficiency and effectiveness of the proposed algorithm. Hemamalini and Simon (2010) proposed a study for solving economic load dispatch problem with non-smooth cost functions by using ABC algorithm. Nayak et al. (2009) applied ABC to economic load dispatch problem with ramp rate limits and prohibited operating zones and concluded that the proposed methodology was found to be robust, fast converging and more proficient over other existing techniques. Tahooneh and Ziarati (2011) used ABC to solve stochastic resource constrained project scheduling problem. Pal et al. (2011) described an ABC to solve the problem of integrated procurement, production and shipment planning for a supply chain. Hemamalini and Simon (2011) employed ABC to solve dynamic economic dispatch problem which is an important dynamic problem in power system operation and control. Sundar and Singh (2010a) applied ABC to the quadratic minimum spanning tree problem which is an extension of the minimum spanning tree problem. Sundar et al. (2010) presented an ABC algorithm for the 0–1 multidimensional knapsack problem and computational results demonstrated that ABC not only produces better results but converges very rapidly in comparison with other swarm-based approaches. Sundar and Singh (2010b) developed an ABC algorithm to solve the quadratic multiple knapsack problem which can be considered as an extension of two well known knapsack problems viz, multiple knapsack problem and quadratic knapsack problem. Tasgetiren et al. (2010) described a discrete ABC algorithm hybridized with an iterated greedy and iterated local search algorithms embedded in a variable neighbourhood search procedure based on swap and insertion neighbourhood structures. Singh (2009) proposed an ABC algorithm for the leaf-constrained minimum spanning tree problem. Kumar et al. (2010) applied ABC to the minimisation of supply chain cost with embedded risk. Singh and Sundar (2012) described an ABC algorithm for the minimum routing cost spanning tree problem. Ozcan and Esnaf (2011) investigated a heuristic approach based on ABC for shelf space allocation problem by using a model which considers the space and cross elasticity. Tasgetiren et al. (2011a) presented a discrete ABC to solve the economic lot scheduling problem under extended basic period approach and power of-two policy. Vishwa et al. (2010) illustrated the complexities involved in resolving a remanufacturing problem and formulated a mathematical model, and then used ABC for solving this problem which is an NP hard problem. Liu et al. (2010) constructed a semi-variance model of real estate investment portfolio based on risk preference coefficient and solved this model by using an ABC. Li et al. (2011b) used ABC for reliability analysis of engineering structures and demonstrated by four examples that the present method is reliable and accurate in reliability analysis of engineering structures. Safarzadeh et al. (2011) introduced a core reloading technique using ABC, in the context of finding an optimal configuration of fuel assemblies. Uthitsunthorn et al. (2011) presented the optimal coordination of overcurrent relays by using ABC algorithm. Abu-Mouti and El-Hawary (2009) described a modified ABC for optimal distributed generation sizing and allocation in distribution systems. Lei et al. (2010b) developed a new ABC for the multiple sequence alignment problem and computational results demonstrated the superiority of the new algorithm over GA and PSO for many sequences with different length and identity. Ma and Lei (2010) proposed a path planning method combined time rolling window strategy and ABC algorithm for the global path planning of mobile robot under the dynamic uncertain environment. Han et al. (2011) applied a discrete ABC algorithm to the blocking flow shop scheduling problem with makespan criterion in which the proposed method utilizes discrete job permutations to represent food sources and applies discrete operators to generate new food sources for the employed bees, onlookers and scouts. Baykasoğlu et al. (2007) used ABC to solve generalised assignment problem which is an NP-hard problem and found that it is very effective in solving small to medium sized generalized assignment problems. Noaman and Jaradat (2011) solved the shortest common supersequence, which is a classical problem in the field of strings and classified as NP-Hard problem, by using ABC algorithm. Alzaqebah and Abdullah (2011b) presented an investigation of selection strategies upon the ABC algorithm in examination timetabling problems.

Vivekanandan et al. (2011) implemented ABC for job scheduling in grid in which ABC dynamically generates an optimal schedule so as to complete the task in minimum period of time as well as utilizing the resources in an efficient way. Ji and Wu (2011) described an improved ABC algorithm for the capacitated vehicle routing problem with time-dependent travel times. Zhang and Wu (2011a) proposed an ABC algorithm for the job shop scheduling problem with random processing times. Bolaji et al. (2011) presented the adaption of the ABC algorithm for solving timetabling problems, with particular focus on the curriculum-based course timetabling. Anandhakumar et al. (2011) proposed an ABC algorithm to generator maintenance scheduling in competitive market. Brajevic (2011) described ABC algorithm for the capacitated vehicle routing problem. Alzaqebah and Abdullah (2011a) concerned how to use ABC to solve examination timetabling problems which is known as an NP-hard problem. Shi et al. (2011) proposed a modified ABC algorithm to tackle the layout design problem of satellite module. Ajorlou et al. (2011) introduced an optimization approach for a multi-product CONWIP-based manufacturing system based on ABC approach.

Applications of ABC in electronics, software and control engineering areas can be given as:

In electronics; Haris et al. (2012) proposed two novel and computationally efficient metaheuristic algorithms based on ABC for multi-user detection in turbo trellis coded modulation based space division multiple access orthogonal frequency division multiplexing system. Manoj and Elias (2011) described an approach based on ABC for the design of multiplierless nonuniform filter bank transmultiplexer. Kockanat et al. (2011) developed an approach for the cancellation of noise on mitral valve Doppler signal using IIR filters designed with ABC. Bernardino et al. (2010) employed ABC for efficient load balancing for a resilient packet ring which is a standard for optimising the transport of data traffic over optical fiber ring networks. Karaboga et al. (2011a) described a new method based on ABC for determining the Schottky barrier height, ideality factor and series resistance of a Schottky barrier diode model using forward current-voltage characteristics. Kadioglu et al. (2010) introduced ABC based component value selection method for analog active filters. Wang et al. (2010a) proposed a set of RF modulation methods to improve the accuracy of localization by utilizing the receive signal strength indication and employed ABC to optimize the location estimation in the indoor environment. Rashedi et al. (2011b) proposed a novel approach based on ABC for solving routing and wavelength assignment problem which is known to be an NP-hard problem. Rashedi et al. (2011a) used ABC algorithm to solve dynamic routing and wavelength assignment problem by minimizing the blocking probability for a sequence of arrival connection requests subject to total number of wavelengths in optical network and wavelength continuity constraints. Delican et al. (2010) studied on the usage of ABC algorithm in electronic circuit design and tested its performance on the design of a CMOS inverter considering transient performance. Akdagli et al. (2011) obtained a novel and simple expression for resonant length to calculate the resonant frequency of C-shaped compact microstrip antennas operating on UHF band applications with the aid of ABC. Akdagli and Toktas (2010) applied ABC to obtain a new, simple and accurate expression for the resonant length in calculating resonant frequency of H-shaped compact microstrip antennas at UHF frequencies applications. Toktas et al. (2011) used ABC to obtain simple formulas for calculating resonant frequencies of C and H shaped compact microstrip antennas. Karaboga and Cetinkaya (2011) described a novel approach based on ABC for the design of adaptive FIR and IIR filters. Sabat et al. (2010) applied ABC for small signal model parameter extraction of MESFET and demonstrated that this technique extract accurately the 16-element small signal model parameters of MESFET. Haris et al. (2010) proposed two novel and computationally efficient metaheuristic algorithms based on ABC for multi-user detection in turbo trellis coded modulation based space division multiple access orthogonal frequency division multiplexing system. Rao et al. (2010b) presented a new idea for edge enhancement using hybridized smoothening filters and introduced a promising technique of obtaining best hybrid filter using ABC. Karaboga (2009) presented a new design method based on ABC algorithm for digital IIR filters and its performance was compared with that of a conventional optimization algorithm (LSQ-nonlin) and PSO algorithm. Chaves-Gonzalez et al. (2010) used ABC to deal with the frequency assignment problem which is a telecommunication problem. Sabat et al. (2009) applied ABC for analog circuit synthesis. Deng et al. (2011) described a new mapping algorithm based on ABC to solve the problem of energy aware mapping optimization in network-on-chip design. Basu and Mahanti (2010) described a method of synthesis of uniform circular array antenna using ABC algorithm. Demirkale et al. (2010) exploited ABC algorithm for optimizing the operations of chip mounter machines which are used for printed circuit board assembly. Taspinar et al. (2011b) proposed a partial transmit sequences(PTS) based on ABC to reduce the computational complexity of PTS in the multicarrier code division multiple access systems. Taspinar et al. (2011a) investigated a PTS based on ABC for reducing the computational complexity of the PTS in the OFDM system. Wang et al. (2010c) developed a peak to average power ratio reduction technique based on PTS and modified ABC to search the better combination of phase factors. Karaboğa et al. (2011) proposed IIR filter design by using ABC for eliminating anatomic and electronic noises on mitral valve ultrasonic Doppler sound signal. Karaboga et al. (2011b) designed IIR filters by ABC for the noise elimination on transcranial Doppler signals. Basu and Mahanti (2011) described a method for synthesis of scanned and broadside linear array antenna based on ABC. Wu et al. (2011c) proposed a new method for calculating the roundness error based on ABC algorithm.

In software engineering; Kilic et al. (2011) proposed an approach for solving automated software refactoring problem which is a "hard" combinatorial optimization problem of the search-based software engineering field. AdiSrikanth et al. (2011) introduced a software test case optimization technique based on ABC algorithm. Koc et al. (2012) introduced ABC for solving automated maintenance of object-oriented software system designs via refactoring which is a performance demanding combinatorial optimization problem. Dahiya et al. (2010) presented an ABC based novel search technique for automatic generation of structural software tests. Liang and Ming (2011) studied on using two-tier bitwise interest oriented QRP with ABC optimization to reduce message flooding and improve recall rate for a small world peer-to-peer system. Mala et al. (2010) applied ABC to software test suite optimization which is one of the most important problems in software engineering research. Bacanin et al. (2010) described an object-oriented software system for continuous optimization by a modified ABC metaheuristic. Pacurib et al. (2009) explored the possibility of using an improved variant of ABC in solving sudoku puzzles. Suri and Kalkal (2011) introduced a review of applications of ABC algorithm in the field of software testing. Soimart and Pongcharoen (2011) presented the development of an automated MLD programming tool that apply ABC and reports the influence of ABC's parameters configuration on its performance. Li and Ma (2011) proposed an ABC algorithm based solution method for logic reasoning. Bacanin et al. (2011) studied on the performance of object-oriented software system for improved ABC optimization.

In control engineering; Karaboga and Akay (2010) studied on the PID controller design by using ABC and compared its performance with harmony search and the bees algorithms. Gao et al. (2010b) described a novel chaos control approach based on ABC in a non-Lyapunov way, for discrete chaotic systems with rational fraction. Gao et al. (2010d) proposed to solve the online synchronization problem for uncertain discrete chaotic systems by using ABC in a non-Lyapunov way. Gao et al. (2010c) introduced an novel optimal PID tuning and on-line tuning method based on ABC for optimum adaptive control in a non-Lyapunov way. Gao et al. (2010a) described an ABC to identify the uncertain parameters and time-delays of nonlinear chaotic systems. Abachizadeh et al. (2010a) proposed an efficient method based on ABC for optimal tuning PID controllers. Yan and Li (2011) developed an effective refinement ABC optimization algorithm based on chaotic search and applied for PID control tuning. Shayeghi and Ghasemi (2011) proposed ABC algorithm for the design of PID type controller for the solution of the load frequency control problem. Ercin and Coban (2011) compared the performance of ABC with the bees algorithms for PID controller tuning.

Protein structure optimization is also encountered: Bahamish et al. (2009) described a method based on ABC for the prediction of protein tertiary structure in which ABC algorithm was adapted to search the protein conformational search space to find the lowest free energy conformation. Lin and Lee (2009) proposed a modified ABC algorithm to determine the protein structure from sequence. Bahamish and Abdullah (2010) used the ABC algorithm to predict the tertiary structure of C-peptide of ribonuclease A by searching the conformational search space to locate the lowest free energy conformation. Wu et al. (2011a) introduced an approach based on ABC algorithm for estimating the parameters of non-linear rational models.

4 Discussion and conclusion

The summary of studies on ABC is presented in Tables 1 and 2. The former table shows the modifications on ABC and the publications related to ABC in terms of application areas are given in the later one. From these tables, it can be easily observed that, the growth of this field has exceeded the expectations, despite the fact that ABC is just 5 years old. By looking at the papers that we reviewed, the core of the work on ABC has focused on algorithmic and application aspects, it should be mentioned that there is still much more to do in this area. We believe that some topics are worth investigating within the next years. Particularly, self-adaptation of control parameters and theoretical studies are the first topics to be interested in. The design of ABC with no parameters that have to be fine-tuned by the user is another topic which is worth studying. There is not much theoretical work on ABC in general and the lack of research on theoretical aspects of ABC is, by no means, surprising. It would be interesting to perform a theoretical study of the run-time and convergence properties of a ABC. Other aspects such as the fitness landscapes and dynamics of a ABC are also very attractive theoretical research topics.

Although ABC has great potential, it was clear to the scientific community that some modifications to the original structure are still necessary in order to significantly improve its performance. And also ABC can be used as an evolutionary framework into which different traditional or modern heuristic algorithmic components are integrated. ABC can be also applied for optimization in dynamic and uncertain environments. In order to improve the perform of ABC in terms of convergence, new neighbor production mechanisms can be proposed. Diversity is provided by scout production. New strategies can be described for scout production phase. Moreover, this strategy can be operated adaptively depending on the dynamics of the search. For the distribution of onlookers to the sources, new selection strategies which enhances the performance of ABC can be described.

Like all other evolutionary optimization approaches, ABC also has some drawbacks. For example since it does not uses an operator like crossover as employed in GA or DE the distribution of a good information between solutions is not at a required level. This causes the

Table 1 Different versions of ABC algorithm

ABC	Studies
Continuous	Karaboga (2005), Basturk and Karaboga (2006), Karaboga and Basturk (2007b, 2008), Li et al. (2010c, 2011a), Karaboga and Akay (2009a,b), Akay and Karaboga (2009a, 2010), Chu et al. (2011), Ruiz-Vanoye and Daz-Parra (2011), Mala et al. (2009), Krishnanand et al. (2009), Mohammed and El-Abd (2012), Dongli et al. (2011), Kang et al. (2011a), Aderhold et al. (2010), Bao and Zeng (2009), Pansuwan et al. (2010), Guo et al. (2011), Mohan and Baskaran (2011), Alam et al. (2010), Lee and Cai (2011), Diwold et al. (2011), Ho and Yang (2009), Banharnsakun et al. (2011a), Gao and Liu (2011, 2012), Rajasekhar et al. (2011a,b), Raziuddin et al. (2011), Zhu and Kwong (2010), Lei et al. (2010a), Xu and Lei (2010), Liu and Cai (2009), Bi and Wang (2011), Stanarevic (2011), Zou et al. (2011), Wu et al. (2011d)
Combinatorial/discrete	Karaboga and Gorkemli (2011),Szeto et al. (2011), Yeh and Hsieh (2011), Tasgetiren et al. (2010, 2011a,b), Li et al. (2011b,e,f), Pan et al. (2011), Ziarati et al. (2011), Hemamalini and Simon (2010, 2011), Nayak et al. (2009), Tahooneh and Ziarati (2011), Pal et al. (2011), Sundar and Singh (2010a,b), Sundar et al. (2010), Singh (2009), Kumar et al. (2010), Singh and Sundar (2012), Ozcan and Esnaf (2011), Vishwa et al. (2010), Liu et al. (2010), Safarzadeh et al. (2011), Uthitsunthorn et al. (2011), Abu-Mouti and El-Hawary (2009), Lei et al. (2010b), Ma and Lei (2010), Han et al. (2011), Banharnsakun et al. (2011),Shi et al. (2010b), Wei et al. (2011), Li et al. (2011e), Baykasoğlu et al. (2007), Noaman and Jaradat (2011), Alzaqebah and Abdullah (2011a,b), Vivekanandan et al. (2011), Ji and Wu (2011), Zhang and Wu (2011a), Bolaji et al. (2011), Anandhakumar et al. (2011), Brajevic (2011), Shi et al. (2011), Ajorlou et al. (2011)
Hybrid	Duan et al. (2009, 2010), Zhao et al. (2010b), Kang et al. (2009a,b, 2010, 2011b), Marinakis et al. (2009), Tsai et al. (2010), Li and Chan (2011), Sundar and Singh (2012), El-Abd (2011), Schiffmann and Sebastiani (2011), Li et al. (2011d), Alzaqebah and Abdullah (2011c), Shi et al. (2010a), Jatoth and Rajasekhar (2010), Ozturk and Karaboga (2011), Zhang et al. (2011b), Zhong et al. (2011), Oner et al. (2011), Banharnsakun et al. (2010a), Gao and Han (2010), Yeh et al. (2011), Pulikanti and Singh (2009), Borovska and Yanchev (2009), Xiao and Chen (2011), Bin and Qian (2011), Sharma and Pant (2011), Li and Jian-chao (2011), Rajasekhar et al. (2011c)
Chaotic	Zhang et al. (2011c,d,e),Xu et al. (2010), Lin et al. (2009), Ayan and Kilic (2011), Alatas (2010), Hong (2011), Wu and Fan (2011), Yan and Li (2011)
Binary/integer	Akay and Karaboga (2009b), Kashan et al. (2011), Wang et al. (2010b)
Multi-objective	Omkar et al. (2011a,b), Akbari et al. (2011), Rubio-Largo et al. (2011), Gonzlez-lvarez et al. (2011), Atashkari et al. (2011), Arsuaga-Rios et al. (2011), Hedayatzadeh et al. (2010), Zhang et al. (2011a), Zou et al. (2012)
Constrained	Karaboga and Akay (2011), Brajevic et al. (2010), Mezura-Montes et al. (2010), Mezura-Montes and Velez-Koeppel (2010), Karaboga and Basturk (2007a), Akay and Karaboga (2012), Stanarevic et al. (2010), Brajevic et al. (2011), Tuba et al. (2011)
Parallel and cooperative	Subotic et al. (2010), Zou et al. (2010a,b), El-Abd (2010), Tsai et al. (2009), Vargas Bentez and Lopes (2010), Narasimhan (2009), Parpinelli et al. (2010), Luo et al. (2010), Banharnsakun et al. (2010b), Subotic et al. (2011)

convergence performance of ABC for local minimum to be slow. This topic can be searched and its convergence performance can be improved.

Symbolic regression, which is a process of obtaining a mathematical model using given finite sampling of values of independent variables and associated values of dependent variables, is a very important practical problem. ABC has been not applied for symbolic regression problem, so far. An extended version of ABC can be improved for these type problems.

Figure 2 demonstrates the distribution of publications related to ABC with respect to years. It is very clear that the number of publications in the literature increases exponentially.

Table 2 Application areas of ABC algorithm

Area	Publication
Neural networks	Yeh and Hsieh (2012), Irani and Nasimi (2011), Ozkan et al. (2011), Karaboga and Ozturk (2009), Parmaksizoglu and Alci (2011), Kurban and Besdok (2009), Karaboga et al. (2007), Karaboga and Akay (2007), Garro et al. (2011), Hsieh et al. (2011), Kumbhar and Krishnan (2011), Shah et al. (2011), Omkar and Senthilnath (2009)
Industrial engineering	Szeto et al. (2011), Yeh and Hsieh (2011), Tasgetiren et al. (2010, 2011a,b), Li et al. (2011b,e,f), Pan et al. (2011), Ziarati et al. (2011), Hemamalini and Simon (2010), Nayak et al. (2009), Tahooneh and Ziarati (2011), Pal et al. (2011), Hemamalini and Simon (2011), Sundar and Singh (2010a,b), Sundar et al. (2010), Singh (2009), Kumar et al. (2010), Singh and Sundar (2012), Ozcan and Esnaf (2011), Vishwa et al. (2010), Liu et al. (2010), Safarzadeh et al. (2011), Uthitsunthorn et al. (2011), Abu-Mouti and El-Hawary (2009), Lei et al. (2010b), Ma and Lei (2010), Han et al. (2011), Baykasoğlu et al. (2007), Noaman and Jaradat (2011), Alzaqebah and Abdullah (2011a,b), Vivekanandan et al. (2011), Ji and Wu (2011), Zhang and Wu (2011a), Bolaji et al. (2011), Anandhakumar et al. (2011), Brajevic (2011), Shi et al. (2011), Ajorlou et al. (2011)
Mechanical engineering	Samanta and Chakraborty (2011), Rao and Pawar (2009, 2010a,b), Hetmaniok et al. (2010), Rao et al. (2010a), Rao and Patel (2011a)
Electrical engineering	Yousefi-Talouki et al. (2010), Gozde and Taplamacioglu (2011), Abu-Mouti and El-Hawary (2010), Ozturk et al. (2010), Cobanli et al. (2010), Chatterjee et al. (2010), Abachizadeh et al. (2010b), Sumpavakup et al. (2010), Linh and Anh (2010), Doğan and Alçı (2011), Ayan and Kılıç (2011a,b), Özyön et al. (2011a), Rao et al. (2008), Özyön et al. (2011b), Bijami et al. (2011), Shayeghi et al. (2011), Dutta et al. (2011), Eke et al. (2011), Ravi and Duraiswamy (2011), Baijal et al. (2011), Lalitha et al. (2010), Rao (2010), de Oliveira et al. (2009), Sarma and Rafi (2011)
Electronics engineering	Haris et al. (2010, 2012), Manoj and Elias (2011), Kockanat et al. (2011), Bernardino et al. (2010), Karaboga et al. (2011a), Kadioglu et al. (2010), Wang et al. (2010a,c), Rashedi et al. (2011a,b), Delican et al. (2010), Akdagli et al. (2011), Akdagli and Toktas (2010), Toktas et al. (2011), Karaboga and Cetinkaya (2011), Sabat et al. (2009, 2010), Rao et al. (2010b), Karaboga (2009), Chaves-Gonzalez et al. (2010), Deng et al. (2011), Basu and Mahanti (2010, 2011), Demirkale et al. (2010), Taspinar et al. (2011a,b), Karaboğa et al. (2011), Karaboga et al. (2011b)
Control engineering	Gao et al. (2010b,c,d), Karaboga and Akay (2010), Ercin and Coban (2011), Gao et al. (2010a), Abachizadeh et al. (2010a), Yan and Li (2011), Shayeghi and Ghasemi (2011)
Civil engineering	Rao and Patel (2011b), Şahin et al. (2011), Rashidi et al. (2011), Zielonka et al. (2011), Mandal et al. (2011), Gomez-Iglesias et al. (2010), Sonmez (2011a,b), Yao et al. (2010), Hadidi et al. (2010)
Software engineering	Kilic et al. (2011), AdiSrikanth et al. (2011), Koc et al. (2012), Dahiya et al. (2010), Liang and Ming (2011), Mala et al. (2010), Bacanin et al. (2010, 2011), Pacurib et al. (2009), Suri and Kalkal (2011), Soimart and Pongcharoen (2011), Li and Ma (2011)
Image processing	Benala et al. (2009), Chidambaram and Lopes (2009, 2010), Nebti and Boukerram (2010), Zhang and Wu (2011b,?), Xu and Duan (2010), Ma et al. (2011), Zhiwei et al. (2011), Akay and Karaboga (2011), Taherdangkoo et al. (2010), Zhao et al. (2010a), Horng and Jiang (2010), Horng (2011), Cuevas et al. (2012), Çivicioğlu (2011), Shokouhifar and Abkenar (2011), Wang (2011), Ye et al. (2011)
Data mining	Karaboga and Ozturk (2010, 2011), Zhang et al. (2010), Karaboga et al. (2010), Wu et al. (2011b), Celik et al. (2011), Hsieh and Yeh (2011), Zhang et al. (2011f), Li et al. (2011c), Zhao and Zhang (2011), Babu et al. (2011), Selvakumar and Nazer (2011), Abedinia et al. (2011), Babu and Rao (2010a), Suguna and Thanushkodi (2011), Shukran et al. (2011), Shokouhifar and Sabet (2010), Sridhar et al. (2010), Babu and Rao (2010b)

Table 2 Continued

Area	Publication
Sensor networks	Mini et al. (2010), Udgata et al. (2009), Ozturk et al. (2011), Mini et al. (2011), Okdem et al. (2011), Öztürk et al. (2012)
Protein structure	Bahamish and Abdullah (2010), Wu et al. (2011a), Bahamish et al. (2009), Lin and Lee (2009)

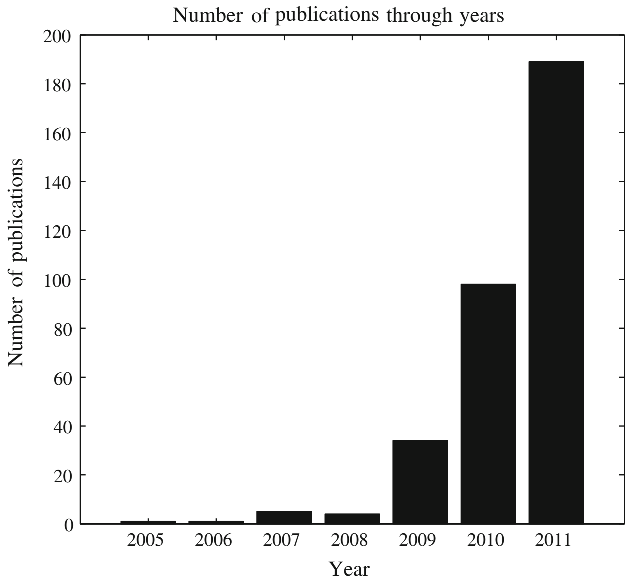

Fig. 2 Number of publications through years

Considering the current level of the research related with this area, we expect a lot of more research study within the next few years.

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