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A survey: algorithms simulating bee swarm intelligence

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Abstract Swarm intelligence is an emerging area in the field of optimization and researchers have developed various algorithms by modeling the behaviors of different swarm of animals and insects such as ants, termites, bees, birds, fishes. In 1990s, Ant Colony Optimization based on ant swarm and Particle Swarm Optimization based on bird flocks and fish schools have been introduced and they have been applied to solve optimization problems in various areas within a time of two decade. However, the intelligent behaviors of bee swarm have inspired the researchers especially during the last decade to develop new algorithms. This work presents a survey of the algorithms described based on the intelligence in bee swarms and their applications.

Keywords Bee swarm intelligence · Task allocation · Bee foraging · Bee mating · Collective decision

1 Introduction

The term swarm is used for an aggregation of animals such as fish schools, birds flocks and insect colonies such as ant, termites and bee colonies performing collective behavior. The individual agents of a swarm behave without supervision and each of these agents has a stochastic behavior due to her perception in the neighborhood. Local rules, without any relation to the global pattern, and interactions between self-organized agents lead to the emergence of collective intelligence called swarm intelligence. Swarms use their environment and resources effectively by collective intelligence. Self-organization is a key feature of a swarm system which results global level (macroscopic level) response by means of low-level interactions (microscopic level). Bonabeau et al. (1999) interpreted the self-organization

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in swarms through four characteristics: (1) *Positive feedback* is a simple behavioral "rules of thumb" that promotes the creation of convenient structures. Recruitment and reinforcement such as trail laying and following in some ant species or dances in bees can be shown as examples of positive feedback. (2) *Negative feedback* counterbalances positive feedback and helps to stabilize the collective pattern. In order to avoid the saturation which might occur in terms of available foragers, food source exhaustion, crowding or competition at the food sources, a negative feedback mechanism is needed. (3) *Fluctuations* such as random walks, errors, random task switching among swarm individuals are vital for creativity and innovation. Randomness is often crucial for emergent structures since it enables the discovery of new solutions. (4) *Multiple interactions* occur since agents in the swarm use the information coming from the other agents so that the information and data spread to all network.

Division of labor, performing tasks simultaneously by specialized agents, is also an important feature of a swarm in many species of social insects as well as self-organization. Flexibility of workers in response to external and internal changes is a striking aspect of division of labor (Calabi 1988; Robinson 1992; Bonabeau et al. 1997; Waibel et al. 2006).

Millonas (1994) also defined five principles to be satisfied by a swarm to have an intelligent behavior:

(a) The swarm should be able to do simple space and time computations (the proximity principle).
(b) The swarm should be able to respond to quality factors in the environment such as the quality of foodstuffs or safety of location (the quality principle).
(c) The swarm should not allocate all of its resources along excessively narrow channels and it should distribute resources into many nodes (the principle of diverse response).
(d) The swarm should not change its mode of behavior upon every fluctuation of the environment (the principle of stability).
(e) The swarm must be able to change behavior mode when the investment in energy is worth the computational price (the principle of adaptability).

Ethologists have modeled the behavior of a swarm with the features described above in both low level and global level (Grosan and Abraham 2006). Recently researchers have been inspired by those models and they have provided novel problem-solving techniques based on swarm intelligence for solving difficult real world problems such as traffic routing, networking, games, industry, robotics, economics and generally designing artificial self-organized distributed problem-solving devices. In 1990s, especially two approaches based on ant colony described by Dorigo et al. (1991) and on fish schooling and bird flocking introduced by Kennedy and Eberhart (1995) have highly attracted the interest of researchers. Both approaches have been studied by many researchers and their new versions have been introduced and applied for solving several problems in different areas. So many papers related with their applications have been presented to the literature and several survey papers regarding these studies can be found in the literature (Eberhart et al. 2001; Sierra and Coello 2006; Blum 2005; Dorigo and Blum 2005).

Although the self-organization and division of labor features defined by Bonabeau et al. (1999) and the satisfaction principles stated by Millonas (1994) for swarm intelligence are strongly and clearly seen in bee colonies, the problem solving techniques based on bee swarm intelligence have began to be introduced recently, especially from the beginning of 2000s. To the best of our knowledge, there is no any survey paper reviewing the algorithms based on the bee swarm intelligence and their applications. Therefore, the aim of this work is to discuss the bee colony system and its manifestation of the features mentioned above; and then to summarize the algorithms simulating the intelligent behaviors in the bee colony and their applications.

2 Bees in nature

A very interesting swarm in nature is honey bee swarm that allocates the tasks dynamically and adapts itself in response to changes in the environment in a collective intelligent manner. The honey bees have photographic memories, space-age sensory and navigation systems, possibly even insight skills, group decision making process during selection of their new nest sites, and they perform tasks such as queen and brood tending, storing, retrieving and distributing honey and pollen, communication and foraging. These characteristics are incentive for researchers to model the intelligent behaviors of bees. Before presenting the algorithms described to use intelligent behaviors and their applications, behavior of the colony is explained below:

Bees are social insects living as colonies. There are three kinds of bees in a colony: drones, queen and workers.

2.1 Queen bee

Queen bee can live several years. She is the only egg-laying female who is the mother of all the members of the colony. The queen usually mates only once in her life and she fertilizes for two or more years by the sperms stored in the mating. After consuming the sperms, she produces unfertilized eggs and one of her daughters is selected as a queen in order to keep on egg-laying. A laid egg hatches into larva, pupate, adult bee, respectively. When the colony is lack of food sources, queen produces new eggs. If the colony becomes too crowded, the queen stops laying. A healthy queen bee can lay 2,000 eggs a day and 175,000–200,000 eggs per year depending on the conditions mentioned.

2.2 Drones

Drones are the fathers of the colony, in other words drones are male bees. They are produced from unfertilized eggs, queens and workers produced from fertilized eggs which are fed differently as larvae. They never live more than 6 months. There are several hundred of drones in the colony in summer times. The primary task of a drone is to fertilize a new queen. Drones die after they mate with the queen.

2.3 Workers

They collect food, store it, remove debris and dead bees, ventilate the hive and guard the hive. Workers make the wax cells in which the queen lays eggs and feed the larvae, drones and queen by special substance or secretion of their salivary glands. The tasks of a worker bee are based on its age and the needs of the colony. In second half of her life, she works as a forager by initially leaving the hive for short flights in order to learn the location of the hive and the environment topology. They live for 6 weeks during summer times and 4–9 months during the winter times.

2.4 Mating-flight

The queen mates during her mating flights far from the nest. A mating flight starts after a dance performed by the queen bee. During the flight the drones follow the queen and mate with her in the air. A drone mates with a queen probabilistically according to queen's speed and fitness of the queen and the drone. Sperm of the drones will be deposited and accumulated in the queen's spermatheca to form the genetic pool of the potential broods to be produced by the queen.

2.5 Foraging

Foraging is the most important task in the hive. Many studies (Von Frisch 1953; Von Frisch and Lindauer 1956; Seeley 1985) have investigated the foraging behavior of each individual bee and what types of external information (such as odor, location information in the waggle dance, the presence of other bees at the source or between the hive and the source) and internal information (such as remembered source location or source odor) affect this foraging behavior. Foraging process starts with leaving the hive of a forager in order to search food source to gather nectar. After finding a flower for herself, the bee stores the nectar in her honey stomach. Based on the conditions such as richness of the flower and the distance of the flower to the hive, the bee fills her stomach in about 30–120 min and honey making process begins with the secretion of an enzyme on the nectar in her stomach. After coming back to the hive, the bee unloads the nectar to empty honeycomb cells and some extra substances are added in order to avoid the fermentation and the bacterial attacks. Filled cells with the honey and enzymes are covered by wax.

2.6 Dance

After unloading the nectar, the forager bee which has found a rich source performs special movements called "dance" on the area of the comb in order to share her information about the food source such as how plentiful it is, its direction and distance and recruits the other bees for exploiting that rich source. While dancing, other bees touch her with their antenna and learn the scent and the taste of the source she is exploiting. She dances on different areas of the comb in order to recruit more bees and goes on to collect nectar from her source. There are different dances performed by bees depending on the distance information of the source: round dance, waggle dance, and tremble dance. If the distance of the source to the hive is less than 100 meters, round dance is performed while the source is far away, waggle dance is performed. Round dance does not give direction information. Incase of waggle dance, direction of the source according to the sun is transferred to other bees. Longer distances cause quicker dances (Hamdan 2008; Mackean 2008). The tremble dance is performed when the foraging bee perceives a long delay in unloading its nectar.

2.7 Nest site selection

While deciding nest site selection, bees pay attention on some issues such as the size of cavity to hold combs, tightness of the cavity, weather conditions and the construction time. The most important issue is that giving a unified decision in all swarm without conflicts. In order to achieve this task, many scout bees working in parallel explore for potential nest sites and share their information about the explored sites with the other scout bees by dancing. From all alternatives, the best is selected by means of the various coalitions of scouts by attracting others via waggle dances of which the strength is proportional to the site quality. A scout prefers the other site that is advertised by dances only if the advertised site is a worthy site after inspecting the site. Inspection progress provides shifting to poor sites (Seeley and Visscer 2006).

2.8 Navigation

Forager bees use a map-like organization of spatial memory for homing, food source search flights. This organization is based on the computations of two experienced vectors, or on viewpoints and landmarks. There are two perspectives of which one certainly true is not known. First one is that bees use stimuli obtained during their flights. The second one is that they encode the spatial information in their dances into their map-like spatial memory (Menzel et al. 2006).

2.9 Task selection

A honeybee colony needs to divide its workforce so that the appropriate number of individuals are allocated for each of the many tasks (Beekman et al. 2007). Bees are specialized in order to carry out every task in the hive. However, there is a controversy about which factors have roles on the specialization of bees, such as their age, hormones (internal factors), individual predisposition coming from their genetic determination (Dornhaus et al. 1998) and also the allocation of tasks can dynamically change. For example, when food is drought, younger nurse bees will also join to foraging process.

Depending on the swarm intelligent behaviors of a bee swarm noted above, several approaches have been introduced and applied to solve problems. In the following section, these approaches and their applications are summarized.

3 Studies based on bee swarm intelligence

Honey bees exhibit many features that can be used as models for intelligent systems. These features include bee dance (communication), bee foraging, queen bee, task selection, collective decision making, nest site selection, mating, floral/pheromone laying, navigation systems.

3.1 Queen bee

Jung (2003) proposed an evolution method called queen-bee evolution simulating the queen-bee role in reproduction process. The method improves the optimization capability of genetic algorithms by enhancing exploitation and exploration processes. Qin et al. (2004) applied queen-bee evolution algorithm to the economic power dispatch problem which is formulated as a nonlinear constrained complex optimization problem. Azeem and Saad (2004) modified queen-bee evolution model by using the weighted crossover operator and applied the algorithm for the tuning of input and output scaling factors of fuzzy knowledge base controller, for two complex non-linear systems and Azeem (2006) applied for four different types of complex non-linear systems. Karci (2004) proposed a crossover operator type inspired by the sexual intercourses of honey bees. The operator selects a queen bee as a parent of crossover by the best fitness, worst fitness and sequentially. Xu et al. (2008) developed Bee Swarm Genetic Algorithm for designing DNA sequences that satisfy some combinatorial and thermodynamic constraints, in which the optimum individual of population selected as a queen bee and a random population is introduced to reinforce the exploitation of Genetic Algorithm (GA) and increase the diversity of population. Lu and Zhou (2008a) proposed a Genetic Algorithm Based on Multi-bee Population Evolutionary (BMGA) algorithm in which one of the populations is produced by BMGA and others are chosen randomly. Queen bee which is the best solution of each population is recombined by a selected individual (drone) via crossover. Xiongm et al. (2008) used the queen-bee crossover in GA to make the procedure more efficient for the label-constrained minimum spanning tree problem.

3.2 Bee dance and communication

Sato and Hagiwara (1997) proposed an improved genetic algorithm named Bee System depending on the behavior of bees. In the model a bee finds feed and then it gives information to the other bees by dancing to work together. Bees correspond to chromosomes of Genetic Algorithm and each chromosome tries to find a good solution individually. When a chromosome is superior, other chromosomes try to find a solution around there using multiple populations. With the experiments, they show that the Bee System has better performance than the conventional genetic algorithm.

Walker (2003) simulated the information sharing and processing models of honeybees and adapt them to information fluctuations that occur within a computer, a local area network, and a wide area network that encompasses the whole Internet.

Gordon et al. (2003) proposed a solution to the problem of pattern formation on a grid, for a group of identical autonomous robotic agents by the communication between the agents. The proposed algorithm called Discrete Bee Dance is a sequence of several coordinated "bee dances" on the grid. By the dance the agents share information and cooperate in order to reach agreements and resolve problems due to their indistinguishability.

Wedde et al. (2004) developed a BeeHive algorithm which has been inspired by the communication in the hive of honey bees and they applied the BeeHive algorithm to the routing in networks. In the algorithm, bee agents travel through network regions called foraging zones and they share information on the network state for updating the local routing tables (Wedde and Farooq 2005a,b). They compared the performance of the BeeHive algorithm to the state-of-art algorithms in Wedde and Farooq (2006). Wedde et al. (2006b) extended the BeeHive algorithm with their security model to counter the security threats of the BeeHive and called the algorithm BeeHiveGuard. Wedde et al. (2006a) integrated the Artificial Immune System and BeeHive algorithm and named the algorithm: BeeHiveAIS. They designed an empirical validation framework in order to compare the BeeHiveAIS and BeeHiveGuard. The results demonstrate that BeeHiveAIS provides the same security level as BeeHiveGuard although the processing and communication costs of the BeeHiveAIS are significantly smaller as compared to BeeHiveGuard. Wang et al. (2007) proposed a QoS unicast routing scheme with always best connected supported based on beehive algorithm.

Wedde et al. (2007) presented a completely decentralized multi-agent approach (termed BeeJamA) on multiple layers where car or truck routing are handled through algorithms adapted from the BeeHive algorithms which in turn have been derived from honey bee behavior. They reported superior performance of BeeJamA over conventional approaches (Wedde et al. 2008).

Navrat (2006) proposed an approach to web search based on a bee hive metaphor comprising of a dance floor, an auditorium, and a dispatch room. Bee Hive Metaphor is a simple model that describes some processes taking place in web search (Navrat and Kovacik 2006). Navrat et al. (2007) used Bee Hive Metaphor for an on-line search of the user's predefined group of pages. Authors claim that the hive determines the best routes of the search and rejects the bad ones by the experiments reported in the paper. However, a comprehensive experimentation has not been performed.

Olague and Puente (2006) proposed a framework called Honey Bee Search Algorithm in which the 3D points communicate between them as in the communication system of honey bees to achieve an improved sparse reconstruction which could be used reliable in further visual computing tasks. From the experiments, the proposed communication system reduces the number of outliers.

3.3 Task allocation

Nakrani and Tovey (2004b) proposed a decentralized honey bee algorithm which dynamically allocates servers to satisfy request loads. They originated from the similarities between server allocation and honey bee colony forager allocation. The algorithm is compared to an omniscient optimality algorithm on simulated request streams and commercial trace data. Honey bee algorithm performed better than static or greedy for highly variable request loads, but greedy outperformed it under low variability. They applied honey bee waggle dance protocol to autonomic server orchestration in internet hosting centers (Nakrani and Tovey 2004a). In 2007, they made a study describing details of the honeybee self-organizing model in terms of information flow and feedback, analyzes the homology between the two problems and derives the resulting biomimetic algorithm for hosting centers (Nakrani and Tovey 2007). From the computational results, the algorithm is regarded as highly adaptive to widely varying external environments and quite competitive against benchmark assessment algorithms.

Gupta and Koul (2007) built an architecture named Swan based on the management of beehives by worker bees and the queen bee in the animal kingdom for network management of IP networks in order to overcome the shortcomings of traditional network management software.

Similarity between honey bee and agents teamwork inspired Sadik et al. (2006) to develop a teamwork architecture to enhance the performance and task execution efficiency of software agents since a limited progress has been made towards efficient task execution mechanisms by group of agents in collaboration and coordination with each other. Sadik et al. (2007) named it Honey Bee teamwork architecture afterwards.

3.4 Collective decision and nest site selection

Yonezawa and Kikuchi (1996) described the principles of collective intelligence generated with the collective cooperative behavior of social honey bees. They examined construction of their Ecological Algorithm and its computational simulation.

Passino (2006) established a mathematical model of the nest-site selection process of honey bee swarms and highlighted the potential implications of the dynamics of swarm decision making.

Gutierrez and Huhns (2008) handled the quorum sensing during nest site selection in the area of design diversity of software fault tolerance.

3.5 Mating, marriage and reproduction

Abbass (2001a) presented an optimization algorithm model based on the marriage in honey-bees (MBO). 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). Abbass applied the model to a fifty propositional satisfiability problems (SAT) with 50 variables and 215 constraints. Abbass (2001c) developed two versions of the proposed algorithm which were incorporated with a well known heuristic for SAT. The two heuristics employed for each version are GSAT and random walk. Abbass (2001c) compared its behavior on 3-SAT against both heuristics alone. Abbass (2001b) made a different modification on the MBO algorithm. In this variation, the colony contains a single queen with multiple workers and the algorithm is applied to 3-SAT problems, where each constraint contains exactly three variables. Teo and Abbass (2001) investigated more conventional annealing approach for the mating-flight process to balance search exploration with search intensification because the algorithm does not exactly implement an annealing approach as it follows a pure exploration strategy. This modified MBO algorithm is tested using a group of randomly generated hard 3-SAT problems to compare its behavior and efficiency against the original implementation. Abbass and Teo (2003) tested a conventional annealing approach as a basis for determining the pool of drones (fathers). This metaheuristic was applied to a data-mining problem by Benatchba et al. (2005) and used to solve partitioning and scheduling problems in code design (Koudil et al. 2007). Curkovic and Jerbic (2007) applied Honey-bees mating algorithm to a non linear Diophantine equation benchmark problem and compared the results to the results of a genetic algorithm. In the same study, they also applied the algorithm to solve a problem of guidance of mobile robot through the space with differently shaped and distributed obstacles. Chang (2006) modified the MBO algorithm for solving combinatorial optimization problems and adapted MBO into an algorithm called "Honey-Bees Policy Iteration" (HBPI) for solving infinite horizon-discounted cost stochastic dynamic programming problems. Some studies in the area of water resources have been implemented by using honey-bee mating algorithm such as optimal reservoir operation (Bozorg Haddad et al. 2006; Afshar et al. 2007; Haddad et al. 2008b), water distribution systems (Haddad et al. 2008a). Amiri and Fathian (2007) integrated self-organizing feature maps neural network (SOM) and honey bee mating algorithm based on K-means algorithm. SOM determines the number of clusters and honey bee mating optimization algorithm finds optimal solution using this cluster number. By the experiments, they claim that the results of simulated data via a Monte Carlo study show that the proposed method outperforms two other methods given in the paper. They also applied the algorithm to a real-world problem of an internet bookstore market segmentation. Fathian et al. (2007); Fathian and Amiri (2008) used this two-stage paradigm in order to overcome local optima problem in clustering and compared the algorithm with other heuristic algorithms in clustering. Yang et al. (2007a) modified MBO by enhancing global convergence capability of the MBO because the calculation process is complex and the speed is slow and named Fast Marriage in Honey Bees Optimization (FMBO). By randomly initializing drones and restricting the condition of iteration, they made the computation process easier and faster. Performance tests of FMBO were conducted on numerical problems. In another study, Yang et al. (2007b) combined the MBO algorithm and the Nelder–Mead method in order to improve its optimization performance by the local characteristic of Nelder–Mead Method. They applied the proposed algorithm (NMFMBO) to Traveling Salesman Problem (TSP) and several public evaluation functions. Marinakis et al. (2008a) introduced a hybrid algorithm (HBMOVRP) based on Honey Bees Mating Optimization for solving the Vehicle Routing Problem, which combines a Honey Bees Mating Optimization (HBMO) algorithm and the Multiple Phase Neighborhood Search - Greedy Randomized Adaptive Search Procedure (MPNS-GRASP) algorithm. Marinakis et al. (2008b) used Hybrid HBMO combining MBO and GRASP for optimally clustering N objects into K clusters. Another hybrid algorithm was presented by Niknam et al. (2008) for multi-objective distribution feeder reconfiguration based on Honey Bee Mating Optimization and fuzzy multi-objective approach. Yang et al. (2007c) proposed

Wolf Pack Search (WPS) algorithm based on the behavior feature of the wolf pack. Using the WPS algorithm into the local search process of Marriage in Honey Bees Optimization algorithm, Wolf Pack Search-Marriage in Honey Bees Optimization (WPS-MBO) algorithm was introduced and some simulations were carried out based on some popular complex Evaluation Functions and Traveling Salesman Problem (TSP). Niknam (2008) presented an approach based on honey-bee mating optimization to estimate the state variables in distribution networks including distributed generators. The method is compared to neural networks, ant colony optimization, and genetic algorithms for two test systems, a network with 34-bus radial test feeders and a realistic 80-bus 20 kV network. Armamentarii (2008) applied an improved version of MBO to ground anti-aircraft weapon system networks.

3.6 Bee Foraging

Sumpter and Broomhead (1998) used nectar foraging to illustrate how process algebras may be used to describe formally the behavior of bees as communicating agents. They established logical properties of a colony and simulated the dynamics of the process by a computer simulation.

The successful applications of the Ant System to the complex engineering problems inspired Lucic and Teodorovic to explore bees' behavior as a source of ideas and models and to develop a Bee System based on foraging behavior of bee colonies for solving difficult combinatorial optimization problems (Lucic and Teodorovic 2001). In the Bee System, the explorers do not have any guidance while looking for food. They are primarily concerned with finding any kind of food source. As a result of such behavior, the scouts are characterized by low search costs and a low average in food source quality. The Bee System was tested through many instances of the Traveling Salesman Problem (Lucic 2002; Lucic and Teodorovic 2002; Teodorovic 2003; Lucic and Teodorovic 2003a Lucia and Teodorovic incorporated the Bee System and the Fuzzy system to handle the uncertainty that sometimes exists in some complex transportation problems. The potential applications of the bee system and the fuzzy ant system in the field of traffic and transportation engineering were discussed (Lucic and Teodorovic 2003b). Teodorovic and Dell (2005) proposed a Bee Colony Optimization (BCO) Metaheuristic for the Ride-matching problem and for the routing and wavelength assignment (RWA) in all-optical networks in Markovic et al. 2007. Vassiliadis and Dounias (2008) applied BCO for finding a high-quality solution for the constrained portfolio optimization problem. Banarjee et al. (2008) incorporated BCO and rough set approach and used this hybrid approach for modelling process and supply chain scheduling. Teodorovic et al. (2006) described a Fuzzy Bee System (FBS) in which the agents (artificial bees) use approximate reasoning and rules of fuzzy logic in their communication and acting. Teodorovic and Dell'orco (2008) used FBS as Travel Demand Management technique for solving ride matching problem and combinatorial problems in general. Wong et al. (2008) also studied BCO on Traveling Salesman Problem. Teodorovic (2008) wrote a review paper about the swarm intelligence systems including bee systems used for transportation engineering.

Tereshko (2000) developed a model of foraging behavior of a honeybee colony based on reaction-diffusion equations and studied how communication in the hive determines this behavior and Tereshko and Lee (2002) studied how mapping the information about the explored environment to the hive determines this behavior. The model utilizes two dominant components of colony's foraging behavior recruitment to and abandonment of the located food source. Tereshko and Loengarov (2005) considered a bee colony as dynamical system gathering information from an environment and adjusting its behavior in accordance to it. In the model, individuals are informed locally and globally. Global informing provides collective intelligence. Loengarov and Tereshko (2008) suggested a model of foraging honey bees that has phase transitions and bistability. The eventual number of foragers depends in a complex way on the bee concentration and on the scouting rate. The results hold relevance for other multi-agent systems with potential jumps in system behavior or efficiency, depending on agent concentration. Ghosh and Marshall (2005) proposed a model of learning and collective decision making in honey bees engaged in foraging. They tend to employ their model for a swarm of robots.

Walker (2004) simulated the foraging behavior of honeybees to facilitate customized routing and congestion avoidance in Internet Services. The model is partitioned into disjoint exploration groups which are, in turn, restricted to sectors of the Internet - this limiting their activities to those HTML providers located within its particular assigned area.

Another algorithm proposed by Wedde and Farooq (2005c) is BeeAdHoc which 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 algorithm employs two types of bees: scouts and foragers, for doing routing in mobile ad hoc networks Wedde et al. (2005). Mazhar and Farooq (2007) systematically analyzed security vulnerabilities of BeeAdHoc and proposed a security framework, BeeSec, for BeeAdHoc that enables it to tackle with the disruptions of malicious nodes in an untrusted MANET. Saleem and Farooq (2007) addressed the issue of security in the challenging MANET environment by developing an AIS based security framework to detect misbehaviour in BeeAdHoc, BeeAIS. They simulated a number of routing attacks. These attacks were successful in a MANET running the original BeeAdHoc protocol. Moreover, they compared BeeAIS system with a cryptographic security system, BeeSec. Saleem et al. (2008) developed mathematical models of two key performance metrics for BeeAdHoc protocol: routing overhead and route optimality. Mazhar and Farooq (2008) proposed a dendritic cell based distributed misbehavior detection system called BeeAIS-DC for BeeAdHoc.

Saleem and Farooq (2007) designed an algorithm called BeeSensor by taking inspiration from relevant features of BeeAdHoc and BeeHive. BeeHive delivers better performance in fixed networks while BeeAdHoc delivers similar or better performance as compared to other adhoc routing algorithms but at least energy cost. As a result, BeeSensor achieves better performance with little energy consumption.

Karaboga introduced a bee swarm algorithm called Artificial Bee Colony (ABC) algorithm simulating foraging behavior of bees Karaboga 2005 in 2005. Basturk and Karaboga compared the performance of ABC algorithm with that of GA Basturk and Karaboga 2006, PSO and PS-EA Karaboga and Basturk 2007b; and DE, PSO and EA Karaboga and Basturk 2008; Karaboga and Akay 2008b on a set of numerical test problems. Karaboga and Akay (2008a) examined the effect of region scaling on algorithms including Artificial Bee Colony algorithm, Differential Evolution Algorithm and Particle Swarm Optimization algorithm. They have extended ABC algorithm for constrained optimization problems in Karaboga and Basturk 2007a and applied ABC for training neural networks Karaboga and Akay 2007; Karaboga et al. 2007. Artificial Bee Colony algorithm was applied to medical pattern classification and clustering problems Karaboga et al. 2008; Ozturk and Karaboga 2008. Fenglei et al. (2007) applied ABC algorithm to Travelling Salesman Problem and studied the control mechanism of local optimal solution. They have carried out the experimental studies on the TSPLIB and improved the global search ability of the algorithm. Singh (2009) used the artificial bee colony algorithm for the Leaf-Constrained Minumum Spanning Tree (LCMST) problem called ABC-LCMST and compared the approach against genetic algorithm, ant-colony optimization algorithm and tabu search. Singh (2009) reported that ABC-LCMST outperforms the other approaches in terms of best and average solution qualities and the computational time. Rao et al. (2008) applied ABC algorithm to network reconfiguration problem in a radial distribution system in order to minimize the real power loss, improve voltage profile and balance feeder load subject to the radial network structure in which all loads must be energized. 14, 33 and 119 bus systems were employed in the experiments and the results were compared against genetic algorithm, differential evolution and simulated annealing. The results obtained by the ABC algorithm were better than the other methods in terms of quality of the solution and computation efficiency. Bendes and Ozkan (2008) used ABC algorithm for solving Direct Linear Transformation (DLT) which is one of the camera calibration methods by establishing relation between 3D object coordinate and 2D image plane linearly. Results produced by the ABC algorithm were compared against Differential Evolution Algorithm (DE). Karaboga (2009) used ABC algorithm in signal processing area for designing digital IIR filters. Qingxian and Haijun 2008 proposed a modification in the initialization scheme by making the initial group symmetrical and employed Boltzmann Selection mechanism instead of roulette for improving convergence ability of the ABC algorithm. Hemamalini and Simon (2008) proposed an economic Load Dispatch with Valve-Point Effect by using the ABC algorithm. Quan and Shi (2008) integrated a search iteration operator based on the fixed point theorem of Contractive Mapping in Banach Spaces with the ABC algorithm in order to improve convergence rate. Pawar et al. (2008a,b,c) applied the ABC algorithm to some problems in mechanical engineering area including multi-objective optimization of electro-chemical machining process parameters, optimization process parameters of abrasive flow machining process and milling process. In order to maximize the exploitation capacity of onlooker stage, Tsai et al. (2008) introduced the Newtonian law of universal gravitation in the onlooker phase of the basic ABC algorithm in which onlookers are selected based on a roulette wheel (Interactive ABC, IABC). Baykasoglu et al. (2007) proposed Artificial Bee Colony Algorithm by utilizing shift neighborhood searches and Greedy Randomized Adaptive Search Heuristic in order to apply generalized assignment problem. They used penalty function approach for handling constraints.

Yang (2005) developed a virtual bee algorithm (VBA) 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. 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 algorithm works for the functions with two-parameters.

Pham et al. (2005) described the Bees Algorithm which mimics the foraging behavior of honey bees. In its basic version, the algorithm performs a kind of neighborhood search combined with random search and can be used for both combinatorial optimization and functional optimization. For neighborhood selection, the highest fitnesses are chosen as selected bees. For recruitment, bees are assigned based on the fitnesses associated with the sites they are visiting. And the elitist bee is selected in order to form the next generation of the colony unlike the process in nature of real bees. Bee Algorithm is applied to complex optimization problems Pham et al. 2006b, optimizing neural networks for identification of wood defects Pham et al. 2006e, optimizing the weights of multi-layer perceptrons Pham et al. 2006c, training the radial basis function networks for control chart pattern recognition Pham et al. 2006a, training the learning vector quantisation networks for control chart pattern recognition Pham et al. 2006d, a welded-beam structure design Pham and Ghanbarzadeh 2007, manufacturing cell formation Pham et al. 2007a, scheduling jobs for a machine Pham et al. 2007d, tuning a fuzzy logic controller for a robot gymnast Pham et al. 2007c, data clustering Pham et al. 2007f, optimizing a support vector machine for wood defect classification Pham et al. 2007e, preliminary design Pham et al. 2007b, some engineering design problems Pham et al. 2007g, Protein Conformational Search Bahamish et al. 2008 and synthesizing multiple beam antenna arrays with digital attenuators and digital phase shifters Guney and Onay 2008. Lee and Darwish (2008) applied Bee Algorithm with weighted sum to environmental/economic power dispatch problem in which both fuel cost and emission are to be simultaneously minimized.

Drias et al. (2005) introduced a meta-heuristic named "Bees Swarm Optimization", based on the behavior of real bees. An adaptation to the features of the MAX-W-SAT problem was introduced to contribute to its resolution. They performed experiments on the hard Johnson benchmark. A comparative study with well known procedures for MAX-W-SAT was presented and BSO outperformed the other evolutionary algorithms especially AC-SAT, an ant colony algorithm for SAT. Sadeg and Drias (2007) presented a parallel version of the Bees Swarm Optimisation (BSO) metaheuristic. and experienced on the performances of the sequential and the parallel algorithms in solving instances of the weighted maximum satisfiability problem.

Chong et al. (2006) described a bee colony optimization algorithm based on foraging and waggle dance and using dance durations to select a new path and the algorithm was applied to job shop scheduling. Chong et al. (2007) utilized an efficient neighborhood structure to search for feasible solutions and iteratively improve on prior solutions. The initial solutions are generated using a set of priority dispatching rules. Experimental results comparing the proposed honey bee colony approach with existing approaches such as ant colony, tabu search and shifting bottleneck procedure on a set of job shop problems are presented. The results indicate the performance of the proposed approach is comparable to other efficient scheduling approaches

In Quijano and Passino 2007a,b, a model of honey bee social foraging was introduced for solving a class of optimal resource allocation problems.

Baig and Rashid (2006) presented Honey Bee Foraging (HOB) algorithm which simulates the food foraging behavior of the honey bees and performs a swarm based collective foraging for fitness in promising neighborhoods in combination with individual scouting searches in other areas. When promising regions are found, the algorithm dynamically relocates scout and forager bees (Baig and Rashid 2007).

Lu and Zhou (2008b) developed Bee Collecting Pollen Algorithm (BBC) by simulating the honeybees' collecting pollen as a global convergence searching algorithm. They used the algorithm for solving TSP.

Ko et al. (2008) proposed a self-adaptive Grid computing protocol called Honeydews which is based on adaptive bee foraging behavior in nature and applied it to Grid applications. They also designed a variant of Honeydews, called HoneySort, for application to Grid parallelized sorting settings using the master-worker paradigm.

3.7 Floral and pheromone laying

Ashlock and Oftelie (2004) proposed a study in order to see if floral constancy which is the tendency to harvest nectar from only one type of flower evolves in the virtual bees. They established a hypothesis that populations with flowers that had nearly equal amounts of nectar available to the bee would not specialize, but populations with flowers that had a large difference in obtainable nectar would specialize in the flower with more nectar available. Purnamadjaja and Russell (2005) described a project to implement necrophoric bee behavior in a robot swarm by pheromone communication. The necrophoric pheromone released by dead bees triggers corpse removal behavior in passing worker bees. In a similar manner, they established an analogy that pheromone will provide a valuable form of communication between robots. In the context of a robot swarm one of the proposed applications for necrophoric behavior is to locate and rescue disabled robots that release a pheromone as a form of distress signal. As the sequence of this work, Purnamadjaja and Russell (2007) inspired from the queen bee pheromone that has a number of crucial functions in a bee colony, such as keeping together and stabilizing the colony. In the context of a robotic system, a group of robots to be guided by a robot leader by the pheromone. The robot leader could release different chemicals to elicit a range of behaviors from other members of the group.

3.8 Navigation

Bees' large scale navigation behavior inspired Bianco (2004) in order to describe a mapping paradigm. Navigation is performed through the use of two distinct sets of landmarks: global landmarks guide roughly the agent to a place, local landmarks guide the agent to perform very precise motion to the final destination. In the context of the paradigm, a map is composed of two distinct levels: (i) the agent navigates from place to place (topological navigation) following the global potential function, (ii) a finer map of the specific place represented by a local potential function when the agent is close to the place. Lemmens et al. (2007a, 2008) presented a non-pheromone-based algorithm inspired by recruitment and navigation strategies of bees and they compared the algorithm to pheromone-based algorithms in the task of foraging. They also developed pheromone based version of their approach (Lemmens et al. 2007b). Walker et al. (1993) modeled a robotic control system on the spatial memory and navigatory behaviors attributed to foraging honey bees in an effort to exploit some of the robustness and efficiency of these insects.

4 Conclusion

The main algorithms developed on the intelligent features of a bee colony and their applications are presented in Table 1. Distribution of publications with respect to years are also given in Fig. 1. From Table 1, it can be easily concluded that the algorithms simulating bee swarm intelligence have been used for solving several problems in many different areas. From Table 1, studies being inspired by the queen bee are utilizing this behavior in parent or elitist selection since the queen bee in the colony is the best equipped individual. Models based on task allocation property are generally used for combinatorial problems due to its nature, but the problem range the model is applicable is not limited to this type of problems and it depends on the model developed. Moreover, an algorithm which has been firstly developed for numerical problems (such as VBA, ABC, BA) can be expanded for combinatorial type problems by suitable modifications.

Also from Fig. 1, it is clear that the interest of researchers in bee colony and the applications of the algorithms proposed on bee swarm intelligence raises day by day and the number of papers in the literature related to bee swarm intelligence increases exponentially.

We hope that this survey will be useful for readers interested in algorithms based on bee swarm intelligence and their applications.

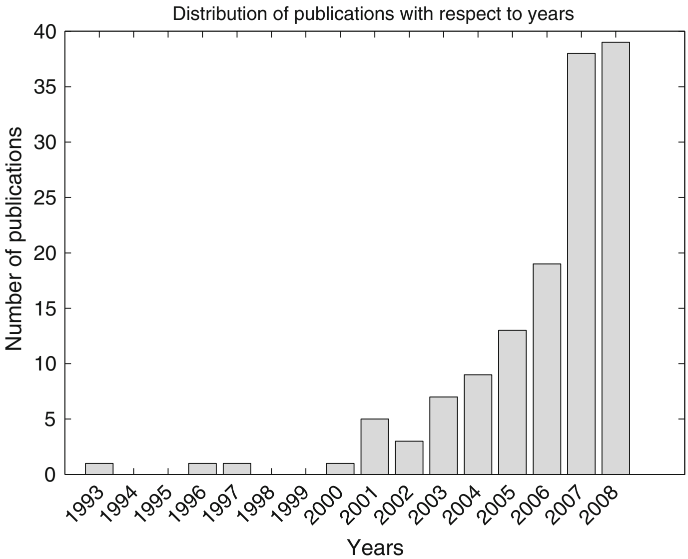

Fig. 1 Distribution of publications with respect to years

Table 1 Categorical view of the algorithms and their applications

Algorithm	Application	Publication
Queen-bee evolution	Improvement on GA	Jung (2003)
	Economic power dispatch	Qin et al. (2004)
	Tuning of input and output scaling factors of fuzzy knowledge base controller for 2 system	Azeem and Saad (2004)
	Tuning of input and output scaling factors of fuzzy knowledge base controller for 4 system	Azeem (2006)
Queen bee based crossover operator for GA	Using queen bee as parent in crossover process of GA	Karci (2004)
	The label-constrained minimum spanning tree problem	Xiongm et al. (2008)
Genetic algorithm based on multi-bee population evolutionary (MBGA)	Numerical problems	Lu and Zhou (2008a)
Bee system	Improvement on GA	Sato and Hagiwara (1997)
Model of information sharing and processing model of bees	Information sharing on LAN, WAN, Internet	Walker (2003)
Discrete bee dance Algorithm	Pattern formation on a grid	Gordon et al. (2003)
Bee hive algorithm	Routing in networks	Wedde et al. (2004)
	Routing in networks	Wedde and Farooq (2005a)
	Routing in networks	Wedde and Farooq (2005b)
	Qos unicast routing scheme	Wang et al. (2007)

Table 1 continued

Algorithm	Application	Publication
BeeHiveGuard	Counter security threads of beehive	Wedde et al. (2006b)
BeeHiveAIS	Security	Wedde et al. (2006a)
BeeJAMa	Routing	Wedde et al. (2007)
Bee hive metaphor	Web search	Navrat (2006)
	On-line search	Navrat et al. (2007)
Honey bee search algorithm	Sparse reconstruction	Olague and Puente (2006)
Ecological algorithm	Pure algorithm, optimal ordering	Yonezawa and Kikuchi (1996)
Systems biology		Passino (2006)
Quorum sensing	Software fault tolerant system	Gutierrez and Huhns (2008)
Decentralized honey bee algorithm	Dynamic server allocation in internet hosting centers	Nakrani and Tovey (2004b)
Honey bee algorithm	Autonomic server orchestration in internet hosting centers	Nakrani and Tovey 2004a
Honey bee algorithm	Hosting centers	Nakrani and Tovey 2007
Swan	Network management of IP networks	Gupta and Koul (2007)
Honey bee teamwork strategy	Software agents	Sadik et al. (2006)
Mating Bee Optimization (MBO)	SAT problems	Abbass (2001a) Abbass (2001c) Abbass (2001b) Teo and Abbass (2001) Abbass and Teo (2003)
	Data mining	Benatchba et al. (2005)
	Partitioning and scheduling problems	Koudil et al. (2007)
	Non linear diophantine equation benchmark problem, guidance of mobile robot through the space with differently shaped and distributed obstacles	Curkovic and Jerbic (2007)
	Combinatorial optimization problems, stochastic dynamic programming	Chang (2006)
	Infinite horizon-discounted cost stochastic dynamic programming problems	Chang (2006)
	Optimal reservoir operation,	Bozorg Haddad et al. (2006); Afshar et al. (2007); Haddad et al. (2008b)
	Water distribution systems	Haddad et al. (2008a)
	Clustering, internet bookstore market segmentation	Amiri and Fathian (2007)
	Local optima problem in clustering	Fathian and Amiri (2008), Fathian et al. (2007)
	Numerical problems	Yang et al. (2007a)
	TSP	Yang et al. (2007b)
	Vehicle routing problem	Marinakis et al. (2008a)
	Clustering	Marinakis et al. (2008b)

Table 1 continued

Algorithm	Application	Publication
	Multiobjective optimization	Niknam et al. (2008)
	Complex evaluation functions and TSP	Yang et al. (2007c)
	Ground anti-aircraft weapon system networks	Armamentarii (2008)
	Estimation of the state variables in distribution networks including distributed generators	Niknam (2008)
Bee system	Pure algorithm	Lucic and Teodorovic (2001)
	TSP problems	Lucic (2002); Lucic and Teodorovic (2002); Teodorovic (2003); Lucic and Teodorovic (2003a)
Bee system + fuzzy ant system	Traffic and transportation engineering	Lucic and Teodorovic (2003b)
Bee colony optimization (BCO)	Ride-matching problem	Teodorovic and Dell (2005)
	The routing and wavelength assignment (RWA) in all-optical networks	Markovic et al. (2007)
	TSP	Wong et al. (2008)
	Constrained portfolio optimization problem	Vassiliadis and Dounias (2008)
	Modelling process and supply chain scheduling	Banarjee et al. (2008)
	Job shop scheduling	Chong et al. (2006)
	Job shop scheduling	Chong et al. (2007)
Fuzzy bee system		Teodorovic et al. (2006)
Reaction-diffusion model	Pure model	Tereshko (2000)
Information-mapping patterns		Tereshko and Lee (2002)
Dynamic system model		Tereshko and Loengarov (2005)
Phase transitions and bistability model		Loengarov and Tereshko (2008)
Foraging model		Ghosh and Marshall (2005)
Honeybee search strategies	Routing and congestion avoidance in Internet services	Walker (2004)
BeeAdhoc	Routing in mobile ad hoc networks	Wedde and Farooq (2005c); Wedde et al. (2005)
BeeSec	Tackle with the disruptions of malicious nodes in an untrusted MANET	Mazhar and Farooq (2007)
BeeAIS	Security in the challenging MANET	Saleem and Farooq (2007)
BeeAIS-DC	Security of manets	Mazhar and Farooq (2008)
BeeAdhoc	Two performance metrics for beeadhoc	Saleem et al. (2008)
BeeSensor=beeAdhoc + beeHive	Routing in networks	Saleem and Farooq (2007)
Artificial bee colony (ABC) algorithm	Numerical problems	Karaboga (2005)

Table 1 continued

Algorithm	Application	Publication
	Performance comparisons on numerical problems	Basturk and Karaboga (2006); Karaboga and Basturk (2007b, 2008); Karaboga and Akay (2008b,a)
	Constrained optimization problems	Karaboga and Basturk (2007a)
	Training neural networks	Karaboga and Akay (2007); Karaboga et al. (2007)
	Medical pattern classification and clustering problems	Karaboga et al. (2008); Ozturk and Karaboga (2008).
	TSP	Fenglei et al. (2007)
	Leaf-constrained minimum spanning tree (LCMST) problem	Singh (2009)
	Network reconfiguration problem	Rao et al. (2008)
	Camera calibration, direct linear transformation (DLT)	Bendes and Ozkan (2008)
	Designing digital IIR filters	Karaboga (2009)
	Numerical problems	Qingxian and Haijun 2008
	Economic load dispatch with valve-point effect	Hemamalini and Simon (2008)
	Numerical problems	Quan and Shi (2008)
	Multi-objective optimization of electro-chemical machining process parameters	Pawar et al. (2008a)
	Optimization process parameters of abrasive flow machining process	Pawar et al. (2008b)
	Optimization process parameters of milling process	Pawar et al. (2008c)
	Numerical problems	Tsai et al. (2008)
	Generalized assignment problem	Baykasoglu et al. (2007)
Virtual bee algorithm (VBA)	Numerical problems	Yang (2005)
Bees algorithm (BA)	Algorithm	Pham et al. (2005)
	Numerical problems	Pham et al. (2006b)
	Optimizing neural networks for identification of wood defects	Pham et al. (2006e)
	Optimizing the weights of multi-layer perceptrons	Pham et al. (2006c)
	Training the radial basis function networks for control chart pattern recognition	Pham et al. (2006a)
	Training the learning vector quantisation networks for control chart pattern recognition	Pham et al. (2006d)
	A welded-beam structure design	Pham and Ghanbarzadeh (2007)
	Manufacturing cell formation	Pham et al. (2007a)
	Scheduling jobs for a machine	Pham et al. (2007d)

Table 1 continued

Algorithm	Application	Publication
	Tuning a fuzzy logic controller for a robot gymnast	Pham et al. (2007c)
	Data clustering	Pham et al. (2007f)
	Optimizing a support vector machine for wood defect classification	Pham et al. (2007e)
	Preliminary design	Pham et al. (2007b)
	Engineering design problems	Pham et al. (2007g)
	Protein conformational search	Bahamish et al. (2008)
	Synthesizing multiple beam antenna arrays	Guney and Onay (2008)
	Multi-objective Environmental/Economic Dispatch	Lee and Darwish (2008)
Bee swarm optimization (BSO)	MAX-W-SAT problem	Drias et al. (2005)
Parallel BSO	MAX-W-SAT problem	Sadeg and Drias (2007)
Honey bee social foraging algorithm	Optimal resource allocation problems	Quijano and Passino (2007a,b)
Honey bee foraging (HBF) algorithm	Numerical problems	Baig and Rashid (2006, 2007)
Developed bee collecting pollen algorithm (BCPA)	TSP	Lu and Zhou (2008b)
Honeyadapt, honeysort	Grid computing	Ko et al. (2008)
Pheromone based Communication	Pure model	Ashlock and Oftelie (2004)
Pheromone communication	Necrophoric bee behavior in a robot swarm	Purnamadjaja and Russell (2005)
Queen bee pheromone	Guiding robots	Purnamadjaja and Russell (2007)
Navigation	Large scale visual precise navigation	Bianco (2004)
Bee algorithm	Multi-agent systems	Lemmens et al. (2007a), Lemmens et al. (2007b, 2008)
Spatial memory	Robotic control system	Walker et al. (1993)

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