Guest Editorial
Special Section on Ant Colony Optimization

ANT COLONY optimization (ACO) is part of a larger field of research termed ant algorithms or swarm intelligence that deals with algorithmic approaches that are inspired by the behavior of ant colonies and other social insects [1]–[3], [5]. Of particular interest are the collective activities of members of a colony, such as foraging, brood care, or nest building, which utilize mechanisms of self-organization, stigmergic communication [5], [13], and task partitioning. Ant algorithms have been proposed as a novel computational model that replaces the traditional emphasis on control, preprogramming, and centralization with designs featuring autonomy, emergence, and distributed functioning. These designs are proving flexible and robust, they are able to adapt quickly to changing environments, and they continue functioning when individual elements fail.

A particularly successful research direction in ant algorithms, ACO [6], [7], [9], [10], is dedicated to their application to discrete optimization problems. ACO is inspired by the foraging behavior of real ants, which use pheromone trails to mark their paths to food sources. In ACO, the discrete optimization problem considered is mapped onto a graph called a *construction graph* in such a way that feasible solutions to the original problem correspond to paths on the construction graph. Then, artificial ants can generate feasible solutions by moving on the construction graph. In practice, colonies of artificial ants search for good solutions for several iterations. Every (artificial) ant of a given iteration builds a solution incrementally by taking several probabilistic decisions. The artificial ants that find a good solution mark their paths on the construction graph by putting some amount of pheromone on the edges of the path they followed. The ants in the next iteration are attracted by the pheromones, i.e., their decision probabilities are biased by the pheromones: in this way, they will have a higher probability of building paths that are similar to paths that correspond to good solutions.

ACO has been applied successfully to a large number of difficult combinatorial optimization problems including traveling salesman problems, quadratic assignment problems, and scheduling problems, as well as to dynamic routing problems in telecommunication networks. Unfortunately, it is difficult to analyze ACO algorithms theoretically, the main reason being that they are based on sequences of random decisions (taken by a colony of artificial ants) that are usually not independent and whose probability distribution changes from iteration to iteration. Accordingly, most of the ongoing research in ACO is of an experimental nature, as this is also reflected by the content of most of the papers published in the literature.

The objective of this Special Section is to collect papers that introduce new methods for ACO, report on especially successful applications of ACO, and describe recent theoretical results in the field.

In September 2000, the workshop *From Ant Colonies to Artificial Ants: Second International Workshop on Ant Algorithms (ANTS 2000)* was held in Brussels, Belgium. Some of the papers that were presented at this workshop have been submitted in revised and enhanced form to this Special Section. Together with additional submissions, 30 papers were received, from which four papers were selected for this Special Section. Each submitted paper has been reviewed by three referees and at least two of the guest editors (the two papers of this Special Section with members of the editorial board as authors were managed by David Fogel, Editor-in-Chief of TRANSACTIONS ON EVOLUTIONARY COMPUTATION, and underwent the normal peer-review process).

The first three papers of this Special Section are application oriented, while the fourth and last paper is about theory. The first paper, by Parpinelli *et al.*, proposes for the first time the use of ACO for tackling the important problem of classification in data mining applications. The authors introduce an algorithm, called Ant-Miner, whose target is the discovery of classification rules. Ant-Miner's main innovation consists in the successful integration of the rather general ACO metaheuristic principles with: 1) a strong use of problem-specific information in the form of heuristic rules for biasing rule construction and 2) with rule-pruning algorithms for removing irrelevant terms from rules. Ant-Miner is evaluated on predictive accuracy and rule simplicity against CN2 [4], a well-known classification-rule discovery algorithm, on six public-domain data sets from the repository maintained at University of California at Irvine. The result is that, while no major differences were found between Ant-Miner and CN2 concerning predictive accuracy, Ant-Miner was able to find significantly simpler (i.e., smaller) rules sets for most of the tested data sets.

The paper by Merkle *et al.* describes an ACO algorithm for the resource-constrained project scheduling problem (RCPSP). The algorithm is tested on a large set of standard benchmark problems from the PSBLIB, which is maintained at the Faculty of Economics and Social Sciences, University of Kiel, Germany. Since the RCPSP is one of the most-studied scheduling problems, it was possible to compare the results of the ACO algorithm to those obtained with many other heuristic approaches that have been proposed in the literature, including genetic algorithms, simulated an-

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nealing, and tabu search. The ACO algorithm performed best on the average over the set of all large instances available in the PSPLIB. Moreover, it was able to find new best solutions for 130 of the 600 test instances. The ACO algorithm proposed includes several new features that are interesting for ACO in general. Examples are the combination of the summation pheromone evaluation method [17] with the normal local evaluation method and the structuring of an ACO algorithm into the following phases: 1) a preprocessing phase for deciding which variant of the ACO algorithm to use; 2) a heuristic guided search phase; 3) the main search without using any heuristic; 4) a convergence phase with increased pheromone evaporation; and 5) a postprocessing phase to improve the best found solutions using other heuristics (e.g., local search).

The third paper, by Solnon, presents Ant-Solver, an ACO algorithm for the solution of constraint satisfaction problems (CSPs). While ACO has so far been applied mainly to optimization problems, this is one of the first attempts to use ACO for solving CSPs, where the goal is to find value assignments to variables such that a set of constraints among the variables is satisfied. Like many ACO algorithms, Ant-Solver integrates a local search phase to improve the solutions constructed by the ants. In addition, Ant-Solver integrates a new preprocessing step that speeds up the convergence of the algorithm especially in the initial search phase. Ant-Solver is evaluated experimentally on a large set of randomly generated binary CSPs, where each constraint involves at most two variables. These tests show that Ant-Solver strongly improves over the performance of random restart local search for the hardest instances, and that Ant-Solver is competitive with earlier proposed local search strategies, such as the min-conflicts heuristic plus random walk, for particular classes of CSPs.

While the first three papers provide additional experimental evidence that the ACO metaheuristic can compete with more established metaheuristics such as tabu search [11], [12], evolutionary computation, or simulated annealing [16], the fourth and last paper of this Special Section provides some of the much-needed theoretical framework that we require to better understand and, therefore, predict the behavior of ACO. In their paper, Stützle and Dorigo prove some convergence properties for a class of ACO algorithms, called $\mathrm{ACO}_{\tau_{\min}}$. In particular, the authors prove that, for any small constant $\epsilon > 0$ and for a sufficiently large number of algorithm iterations t, the probability of finding an optimal solution at least once is $P^*(t) \geq 1 - \epsilon$ and that this probability tends to one for $t \to \infty$. While this is not the first convergence proof for a particular class of ACO algorithms [14], [15], the main importance of the paper resides in the fact that the convergence proofs for $\mathrm{ACO}_{\tau_{\min}}$ are directly extendable to two of the (experimentally) most successful ACO algorithms: Ant Colony System [8] and $\mathcal{MAX}$-$\mathcal{MIN}$ Ant System [18].

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