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-

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 $ACO_{\tau_{\min}}$. 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 $t \rightarrow \infty$. 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 $ACO_{\tau_{\min}}$ are directly extendable to two of the (experimentally) most successful ACO algorithms: Ant Colony System [8] and $\mathcal{MAX}\text{-}\mathcal{MIN}$ Ant System [18].

MARCO DORIGO, *Guest Editor*
Université Libre de Bruxelles
IRIDIA
B-1050 Brussels, Belgium

LUCA MARIA GAMBARDELLA, *Guest Editor*
IDSIA
CH-6928 Manno-Lugano, Switzerland

MARTIN MIDDENDORF, *Guest Editor*
Catholic University of Eichstätt-Ingolstadt
Computer Science Group
D-85072 Eichstätt, Germany

THOMAS STÜTZLE, *Guest Editor*
Darmstadt University of Technology
Computer Science Department
D-64283 Darmstadt, Germany

REFERENCES

[1] E. Bonabeau, M. Dorigo, and G. Theraulaz, *Swarm Intelligence: From Natural to Artificial Systems*. New York: Oxford Univ. Press, 1999.

[2] ——, "Inspiration for optimization from social insect behavior," *Nature*, vol. 406, pp. 39–42, July 6, 2000.

[3] S. Camazine, J.-L. Deneubourg, N. R. Franks, J. Sneyd, G. Theraulaz, and E. Bonabeau, Eds., *Self-Organization in Biological Systems*. Princeton, NJ: Princeton Univ. Press, 2001.

[4] P. Clark and T. Niblett, "The CN2 induction algorithm," *Mach. Learn.*, vol. 3, no. 4, pp. 261–283, 1989.

[5] M. Dorigo, E. Bonabeau, and G. Theraulaz, "Ant algorithms and stigmergy," *Future Gener. Comput. Syst.*, vol. 16, no. 8, pp. 851–871, 2000.

[6] M. Dorigo and G. Di Caro, "The ant colony optimization meta-heuristic," in *New Ideas in Optimization*, I. D. Corne, M. Dorigo, and F. Glover, Eds. London, U.K.: McGraw-Hill, 1999, pp. 11–32.

[7] M. Dorigo, G. Di Caro, and L. M. Gambardella, "Ant algorithms for discrete optimization," *Artif. Life*, vol. 5, no. 2, pp. 137–172, 1999.

[8] M. Dorigo and L. M. Gambardella, "Ant colony system: A cooperative learning approach to the traveling salesman problem," *IEEE Trans. Evol. Comput.*, vol. 1, pp. 53–66, Apr. 1997.

[9] M. Dorigo, V. Maniezzo, and A. Colorni, "The ant system: Optimization by a colony of cooperating agents," *IEEE Trans. Syst. Man Cybern. B*, vol. 26, no. 1, pp. 29–41, Feb. 1996.

[10] M. Dorigo and T. Stützle, Ant Colony Optimization. Cambridge, MA: MIT Press, to be published.

[11] F. Glover, "Tabu search – Part I," *ORSA J. Comput.*, vol. 1, no. 3, pp. 190–206, 1989.

[12] ——, "Tabu search – Part II," *ORSA J. Comput.*, vol. 2, no. 1, pp. 4–32, 1990.

[13] P. P. Grassé, "La reconstruction du nid et les coordinations interindividuelles chez *bellicositermes natalensis et cubitermes sp.* La théorie de la stigmergie: Essai d'interprétation du comportement des termites constructeurs," *Insectes Sociaux*, vol. 6, pp. 41–81, 1959.

[14] W. J. Gutjahr, "A graph-based ant system and its convergence," *Future Gener. Comput. Syst.*, vol. 16, no. 8, pp. 873–888, 2000.

[15] ——, "ACO algorithms with guaranteed convergence to the optimal solution," *Inform. Processing Lett.*, vol. 82, no. 3, pp. 145–153, Feb. 2002.

[16] S. Kirkpatrick, C. D. Gelatt Jr, and M. P. Vecchi, "Optimization by simulated annealing," *Science*, vol. 220, pp. 671–680, May 13, 1983.

[17] D. Merkle and M. Middendorf, "An ant algorithm with a new pheromone evaluation rule for total tardiness problems," in *Real-World Applications of Evolutionary Computing: Proceedings of the EvoWorkshops 2000*, S. Cagnoni, Ed. Berlin, Germany: Springer-Verlag, 2000, vol. 1803, Lecture Notes in Computer Science, pp. 287–296.

[18] T. Stützle and H. H. Hoos, "$\mathcal{MAX}$-$\mathcal{MIN}$ ant system," *Future Gener. Comput. Syst.*, vol. 16, no. 8, pp. 889–914, 2000.

Marco Dorigo (S'92–M'93–SM'96) received the Laurea (Master of Technology) degree in industrial technologies engineering and the doctoral degree in information and systems electronic engineering from Politecnico di Milano, Milan, Italy, in 1986 and 1992, respectively, and the Agrégé de l'Enseignement Supérieur title from the Université Libre de Bruxelles, Brussels, Belgium, in 1995.

From 1992 to 1993, he was a Research Fellow with the International Computer Science Institute, Berkeley, CA. In 1993, he was a NATO-CNR Fellow and, from 1994 to 1996, a Marie Curie Fellow. Since 1996, he has been a Tenured Researcher of the Belgian National Fund for Scientific Research. His current research interests include ant algorithms and swarm intelligence, evolutionary computation, distributed models of computation, and reinforcement learning. In addition, he is interested in the application of these computational paradigms to autonomous robotics, combinatorial optimization, and telecommunications networks problems.

Dr. Dorigo is an Associate Editor of the IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION and IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS. He is a Member of the Editorial Board of numerous international journals, including *Evolutionary Computation*, *Artificial Life*, *Adaptive Behavior*, *Journal of Heuristics*, *Cognitive Systems Research*, and *Journal of Genetic Programming and Evolvable Machines*.

Luca Maria Gambardella (M'91) received the Laurea degree in computer science from the Università degli Studi di Pisa, Pisa, Italy, in 1985.

Since 1988, he has been a Research Director with Istituto Dalle Molle di Studi sull'Intelligenza Artificiale (IDSIA), Manno, Switzerland, a nonprofit research institute affiliated with both the University for Applied Sciences of Southern Switzerland (SUPSI) and the University of Lugano (USI). He is also CSO of AntOptima SA, a company dedicated to transfer Ant Colony Optimization technology to the market. He is leading several research and industrial projects in the area of collective robotics, cooperation, and learning with applications to combinatorial optimization, scheduling, and simulation. His research activities are supported by the Swiss National Foundation, by the Swiss Technology and Innovation Commission, and by the European Commission. His current research interests include machine learning and adaptive systems applied to robotics and optimization problems.