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Marco Dorigo Mauro Birattari
Christian Blum Luca M. Gambardella
Francesco Mondada Thomas Stützle (Eds.)

Ant Colony Optimization and Swarm Intelligence

4th International Workshop, ANTS 2004
Brussels, Belgium, September 2004
Proceedings

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Preface

With its fourth edition, the *ANTS* series of workshops[1] has changed its name. The original *"ANTS – From Ant Colonies to Artificial Ants: International Workshop on Ant Algorithms"* has become *"ANTS – International Workshop on Ant Colony Optimization and Swarm Intelligence"*. This change is mainly due to the following reasons.

First, the term "*ant algorithms*" was slower in spreading in the research community than the term "*swarm intelligence*", while at the same time research in so-called *swarm robotics* was the subject of increasing activity: it was therefore an obvious choice to substitute the term *ant algorithms* with the more accepted and used term *swarm intelligence.*

Second, although *swarm intelligence* research has undoubtedly produced a number of interesting and promising research directions[2], we think it is fair to say that its most successful strand is the one known as "*ant colony optimization*". *Ant colony optimization*, first introduced in the early 1990s as a novel tool for the approximate solution of discrete optimization problems, has recently seen an explosion in the number of its applications, both to academic and real-world problems, and is currently being extended to the realm of continuous optimization (a few papers on this subject being published in these proceedings). It is therefore a reasonable choice to have the term *ant colony optimization* as part of the workshop name.

As mentioned above, this is the fourth edition of the *ANTS* workshops. The series started in 1998 with the organization of *ANTS'98*. On that occasion more than 50 researchers from around the world joined for the first time in Brussels, Belgium to discuss *swarm intelligence* related research, and a selection of the best papers presented at the workshop was published as a special issue of the *Future Generation Computer Systems* journal (Vol. 16, No. 8, 2000). Two years later the experience was repeated with the organization of *ANTS 2000*, which attracted more than 70 participants. The 41 extended abstracts presented as talks or posters at the workshop were collected in a booklet distributed to participants, and a selection of the best papers was published as a special section of the *IEEE Transactions on Evolutionary Computation* (Vol. 6, No. 4, 2002). After these first two successful editions, it was decided to make of *ANTS* a series of biannual events. Accordingly, the third edition was organized in September 2002, in Brussels, Belgium. The success of the workshop and the quality of the papers presented in the second edition had also made it clear that it was the right time to have an official workshop proceedings: the *ANTS 2002* proceedings was

[1] `http://iridia.ulb.ac.be/~ants/`

[2] Think, for example, in addition to the already mentioned swarm robotics, of algorithms for clustering and data mining inspired by the ants' cemetery building behavior, of dynamic task allocation algorithms inspired by the behavior of wasp colonies, of particle swarm optimization, and so on.

published by Springer as Volume 2463 of LNCS, and contained 36 contributions: 17 full papers, 11 short papers, and 8 extended abstracts, selected out of a total of 52 submissions.

The *Ant Colony Optimization and Swarm Intelligence* field is still growing, as testified, for example, by the success of the *1st IEEE Swarm Intelligence Symposium*, held in 2003 in Indianapolis, Indiana, US; or by the steady increase we are observing in the number of submissions to *ANTS* workshops, which resulted in the 79 papers submitted to *ANTS 2004*. This relatively high number of submissions allowed us to set the acceptance threshold for full and short papers at approximately 50%, which guaranteed a fairly high quality of the proceedings, and, at the same time, a reasonably dense workshop program[3]. We are sure that the readers of these proceedings will enjoy the quality of the papers collected in this volume, quality that somehow reflects the growing maturity of the *swarm intelligence* field.

We wish to conclude by saying that we are very grateful to the authors who submitted their works; to the members of the international program committee and to the additional referees for their detailed reviews; to the IRIDIA people for their enthusiasm in helping with organization matters; to the Université Libre de Bruxelles for providing rooms and logistic support; and, more generally, to all those contributing to the organization of the workshop. Finally, we would like to thank our sponsors, the company *AntOptima*[4] and the *Metaheuristics Network*[5], who financially supported the workshop.

June 2004

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Thomas Stützle

[3] In addition to the accepted papers, a small number of posters were selected for presentation: these are works that, although in a rather preliminary phase, show high potential and are therefore worth discussing at the workshop.

[4] More information available at `www.antoptima.com`

[5] A Marie Curie Research Training Network funded by the European Commission. More information available at `www.metaheuristics.org`

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ANTS 2004 was organized by IRIDIA, Université Libre de Bruxelles, Belgium.

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Table of Contents

A Comparison Between ACO Algorithms for the Set Covering Problem ... 1
Lucas Lessing, Irina Dumitrescu, and Thomas Stützle

A VLSI Multiplication-and-Add Scheme
Based on Swarm Intelligence Approaches ... 13
Danilo Pani and Luigi Raffo

ACO for Continuous and Mixed-Variable Optimization ... 25
Krzysztof Socha

An Ant Approach to Membership Overlay Design ... 37
Vittorio Maniezzo, Marco Boschetti, and Mark Jelasity

An Ant Colony Optimisation Algorithm for the Set Packing Problem ... 49
Xavier Gandibleux, Xavier Delorme, and Vincent T'Kindt

An Empirical Analysis of Multiple Objective Ant Colony Optimization
Algorithms for the Bi-criteria TSP ... 61
Carlos García-Martínez, Oscar Cordón, and Francisco Herrera

An External Memory Implementation in Ant Colony Optimization ... 73
Adnan Acan

BeeHive: An Efficient Fault-Tolerant Routing Algorithm Inspired
by Honey Bee Behavior ... 83
Horst F. Wedde, Muddassar Farooq, and Yue Zhang

Competition Controlled Pheromone Update
for Ant Colony Optimization ... 95
Daniel Merkle and Martin Middendorf

Cooperative Transport of Objects of Different Shapes and Sizes ... 106
Roderich Groß and Marco Dorigo

Deception in Ant Colony Optimization ... 118
Christian Blum and Marco Dorigo

Evolution of Direct Communication
for a *Swarm-bot* Performing Hole Avoidance ... 130
Vito Trianni, Thomas H. Labella, and Marco Dorigo

Gathering Multiple Robotic A(ge)nts with Limited Sensing Capabilities ... 142
Noam Gordon, Israel A. Wagner, and Alfred M. Bruckstein

Improvements on Ant Routing for Sensor Networks 154
Ying Zhang, Lukas D. Kuhn, and Markus P.J. Fromherz

Integrating ACO and Constraint Propagation 166
Bernd Meyer and Andreas Ernst

Logistic Constraints on 3D Termite Construction 178
Dan Ladley and Seth Bullock

Modeling Ant Behavior Under a Variable Environment 190
Karla Vittori, Jacques Gautrais, Aluizio F.R. Araújo, Vincent Fourcassié, and Guy Theraulaz

Multi-type Ant Colony: The Edge Disjoint Paths Problem 202
Ann Nowé, Katja Verbeeck, and Peter Vrancx

On the Design of ACO for the Biobjective Quadratic Assignment Problem 214
Manuel López-Ibáñez, Luís Paquete, and Thomas Stützle

Reasons of ACO's Success in TSP 226
Osvaldo Gómez and Benjamín Barán

S-ACO: An Ant-Based Approach to Combinatorial Optimization Under Uncertainty 238
Walter J. Gutjahr

Time-Scattered Heuristic for the Hardware Implementation of Population-Based ACO 250
Bernd Scheuermann, Michael Guntsch, Martin Middendorf, and Hartmut Schmeck

Short Papers

Ad Hoc Networking with Swarm Intelligence 262
Chien-Chung Shen, Chaiporn Jaikaeo, Chavalit Srisathapornphat, Zhuochuan Huang, and Sundaram Rajagopalan

An Ant Colony Heuristic for the Design of Two-Edge Connected Flow Networks 270
Efstratios Rappos and Eleni Hadjiconstantinou

An Experimental Analysis of Loop-Free Algorithms for Scale-Free Networks 278
Shigeo Doi and Masayuki Yamamura

An Experimental Study of the Ant Colony System for the Period Vehicle Routing Problem 286
Ana Cristina Matos and Rui Carvalho Oliveira

An Extension of Ant Colony System
to Continuous Optimization Problems 294
Seid H. Pourtakdoust and Hadi Nobahari

Ant Algorithms for Urban Waste Collection Routing 302
Joaquín Bautista and Jordi Pereira

Ants Can Play Music 310
Christelle Guéret, Nicolas Monmarché, and Mohamed Slimane

Backtracking Ant System for the Traveling Salesman Problem 318
Sameh Al-Shihabi

Colored Ants for Distributed Simulations 326
Cyrille Bertelle, Antoine Dutot, Frédéric Guinand, and Damien Olivier

Dynamic Routing in Mobile Wireless Networks Using ABC-AdHoc 334
Bogdan Tatomir and Leon Rothkrantz

Fuzzy Ant Based Clustering 342
*Steven Schockaert, Martine De Cock, Chris Cornelis,
and Etienne E. Kerre*

How to Use Ants for Hierarchical Clustering 350
Hanene Azzag, Christiane Guinot, and Gilles Venturini

Inversing Mechanical Parameters of Concrete Gravity Dams
Using Ant Colony Optimization 358
Mingjun Tian and Jing Zhou

Large Pheromones: A Case Study with Multi-agent Physical A* 366
*Ariel Felner, Yaron Shoshani, Israel A. Wagner,
and Alfred M. Bruckstein*

Near Parameter Free Ant Colony Optimisation 374
Marcus Randall

Particle Swarm Optimization Algorithm
for Permutation Flowshop Sequencing Problem 382
*M. Fatih Tasgetiren, Mehmet Sevkli, Yun-Chia Liang,
and Gunes Gencyilmaz*

Search Bias in Constructive Metaheuristics and Implications
for Ant Colony Optimisation 390
James Montgomery, Marcus Randall, and Tim Hendtlass

Task Oriented Functional Self-organization of Mobile Agents Team:
Memory Optimization Based on Correlation Feature 398
Sorinel Adrian Oprisan

Towards a Real Micro Robotic Swarm ... 406
Ramon Estaña, Marc Szymanski, Natalie Bender, and Jörg Seyfried

Posters

A Hybrid Ant Colony System Approach for the Capacitated Vehicle Routing Problem ... 414
Lyamine Bouhafs, Amir Hajjam, and Abderrafiaa Koukam

A Swarm-Based Approach for Selection of Signal Plans in Urban Scenarios ... 416
Denise de Oliveira, Paulo Roberto Ferreira Jr., Ana L.C. Bazzan, and Franziska Klügl

Ant Colony Behaviour as Routing Mechanism to Provide Quality of Service ... 418
Liliana Carrillo, José L. Marzo, Lluís Fàbrega, Pere Vilà, and Carles Guadall

Applying Ant Colony Optimization to the Capacitated Arc Routing Problem ... 420
Karl F. Doerner, Richard F. Hartl, Vittorio Maniezzo, and Marc Reimann

Dynamic Optimization Through Continuous Interacting Ant Colony ... 422
Johann Dréo and Patrick Siarry

Dynamic Routing in Traffic Networks Using AntNet ... 424
Bogdan Tatomir, Ronald Kroon, and Leon Rothkrantz

First Competitive Ant Colony Scheme for the CARP ... 426
Philippe Lacomme, Christian Prins, and Alain Tanguy

Hypothesis Corroboration in Semantic Spaces with Swarming Agents ... 428
Peter Weinstein, H. Van Dyke Parunak, Paul Chiusano, and Sven Brueckner

Mesh-Partitioning with the Multiple Ant-Colony Algorithm ... 430
Peter Korošec, Jurij Šilc, and Borut Robič

Author Index ... 433

A Comparison Between ACO Algorithms for the Set Covering Problem

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Abstract. In this paper we present a study of several Ant Colony Optimization (ACO) algorithms for the Set Covering Problem. In our computational study we emphasize the influence of different ways of defining the heuristic information on the performance of the ACO algorithms. Finally, we show that the best performing ACO algorithms we implemented, when combined with a fine-tuned local search procedure, reach excellent performance on a set of well known benchmark instances.

1 Introduction

The Set Covering Problem (SCP) is an $\mathcal{NP}$-hard combinatorial optimization problem that arises in a large variety of practical applications, for example in airline crew scheduling or vehicle routing and facility placement problems [9, 12, 18]. Two Ant Colony Optimization (ACO) approaches for the SCP based on Ant System have been proposed so far [8, 10]; however, their computational performance is relatively poor compared to the state-of-the-art in SCP solving.

In this paper we present the results of a computational study comprising several ACO algorithms including $\mathcal{MAX}$–$\mathcal{MIN}$ Ant System ($\mathcal{MM}$AS) [16], Ant Colony System (ACS) [3], a hybrid between $\mathcal{MM}$AS and ACS [17], as well as Approximate Nondeterministic Tree-Search (ANTS) [14]. Many of the best ACO computational results have been achieved using these algorithms and therefore they serve as good candidates for tackling the SCP. (For details on the full study we refer to [11].) We study the influence of different ways of defining the heuristic information on the performance of the algorithms. We distinguish between the usage of *static* and *dynamic* heuristic information. In the static case, the heuristic information is computed when initializing the algorithm and it remains the same throughout the whole run of the algorithm. In the dynamic case, the heuristic information depends on the partial solution available, hence it has to be computed at each step of an ant's walk. Therefore, it results in a higher computational cost that may be compensated by the higher accuracy of the heuristic values.

The paper is structured as follows. In the next section we introduce the SCP and lower bounds to it. In Section 3, we present some details on the ACO

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algorithms we applied, while in Sections 4 and 5 we give details on the local search and the heuristic information. We present experimental results in Section 6 and conclude in Section 7.

2 Set Covering Problem

The SCP can be formulated as follows. Let $A = (a_{ij})$ be an $m \times n$ 0-1 matrix and $c = (c_j)$ a positive integer n-dimensional vector, where each element c_j of c gives the cost of selecting column j of matrix A. We say that row i is covered by column j, if a_{ij} is equal to 1. The SCP consists of finding a subset of columns of minimal total cost such that all the rows are covered. The SCP is usually formulated as an integer program. Let $N = \{1, \ldots, n\}$ be the index set of the columns and $M = \{1, \ldots, m\}$ be the index set of the rows. The integer programming (IP) formulation of the SCP can be given as follows:

$$z_{SCP} = \min \sum_{j \in N} c_j x_j$$

$$\text{s.t.} \quad \sum_{j \in N} a_{ij} x_j \geq 1, \forall i \in M \tag{1}$$

$$x_j \in \{0, 1\}, \qquad \forall j \in N. \tag{2}$$

We now introduce the Lagrangean relaxation of this problem. For every vector $u = (u_1, \ldots, u_m) \in R_+^m$ we define the Lagrangean relaxation to be:

$$z_{LR}(u) = \min_{x \in \{0,1\}^n} \left[\sum_{j \in N} c_j x_j + \sum_{i \in M} u_i (1 - \sum_{j \in N} a_{ij} x_j) \right] \tag{3}$$

$$= \min_{x \in \{0,1\}^n} \left[\sum_{j \in N} c_j(u) x_j + \sum_{i \in M} u_i \right], \tag{4}$$

where $c_j(u) = c_j - \sum_{i \in M} a_{ij} u_i$ are called *Lagrangean costs.* The Lagrangean relaxation provides a lower bound on the optimal solution of the SCP, i.e. $z_{LR}(u) \leq z_{SCP}, \forall u \geq 0$. The best such lower bound on the optimal solution of the SCP is obtained by solving the *Lagrangean dual* problem, $z_{LD} = \max_{u \geq 0} z_{LR}(u)$. In our experiments, the Lagrangean dual was solved by the subgradient method [7], stopped after at most $100 \cdot m$ iterations as proposed by Yagiura et al. [19].

When we consider the IP formulation, a solution to the SCP is a 0-1 vector. However, when we refer to a solution, we sometimes refer to the set of indices of the variables fixed to one. This should be clear from the context.

3 Ant Colony Optimization for the SCP

Artificial ants in ACO algorithms can be seen as probabilistic construction heuristics that generate solutions iteratively, taking into account accumulated past search experience: pheromone trails and heuristic information on the instance under solution. In the SCP case, each column j has associated a phero-

```
procedure ACOforSCP
   initializeParameters;
   while termination condition is not true do
      for k := 1 to m_a do
         while solution not complete do
            applyConstructionStep(k);
         endwhile
         eliminateRedundantColumns(k);
         applyLocalSearch(k);
      endfor
      updateStatistics;
      updatePheromones;
   endwhile
   return best solution found
endprocedure ACOforSCP
```

Fig. 1. High-level view of the applied ACO algorithms. (For details, see text.)

mone trail τ_j that indicates the learned desirability of including column j into an ants' solution; η_j indicates the heuristic desirability of choosing column j.

In all ACO algorithms an ant starts with an empty solution and constructs a complete solution by iteratively adding columns until all rows are covered. It does so by probabilistically preferring solution components (columns in the SCP case) with high associated pheromone trail and/or heuristic value. Once m_a solutions are constructed and improved by local search, the pheromone trails are updated.

The application of ACO algorithms to the SCP differs from applications to other problems, such as the TSP. First, the solution construction of the individual ants does not necessarily end after the same number of steps for each ant, but only when a cover is completed. Second, the order in which columns are added to a solution does not matter, while in many other applications the order in which solution components are added to a partial solution may be important. Third, in the case of the SCP the solution constructed by the ants may contain redundant solution components which are eliminated before fine-tuning by a local search procedure. This latter feature is also present in two earlier applications of ACO algorithms to the SCP [8, 10]. However, the computational results obtained in [8, 10] are relatively poor, which may be due to the type of ACO algorithm chosen (i.e., Ant System, which is known to perform poorly compared to more recent variants of ACO algorithms). Here, we present the application of more recent ACO variants that exploit a large variety of different types of heuristic information. All these algorithms follow the algorithmic outline given in Figure 1.

3.1 $\mathcal{MAX}$–$\mathcal{MIN}$ Ant System

$\mathcal{MAX}$–$\mathcal{MIN}$ Ant System ($\mathcal{MM}$AS) [16] is at the core of many successful ACO applications. In $\mathcal{MM}$AS solutions are constructed as follows: an ant k ($k = 1, \ldots, m_a$) chooses column j with probability