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Citation analysis and bibliometric approach for ant colony optimization from 1996 to 2010

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ABSTRACT

To build awareness of the development of ant colony optimization (ACO), this study clarifies the citation and bibliometric analysis of research publications of ACO during 1996–2010. This study analysed 12,960 citations from a total of 1372 articles dealing with ACO published in 517 journals based on the databases of SCIE, SSCI and AH&CI, retrieved via the Web of Science. Bradford Law and Lotka's Law, respectively, examined the distribution of journal articles and author productivity. Furthermore, this study determines the citation impact of ACO using parameters such as extent of citation received in terms of number of citations per study, distribution of citations over time, distribution of citations among domains, citation of authors, citation of institutions, highly cited papers and citing journals and impact factor of 12,960 citations. This study can help researchers to better understand the history, current status and trends of ACO in the advanced study of it.

1. Introduction

Ant colony optimization (ACO) is an increasingly important issue in management and optimization to solve difficult and complex real-world problems. Research and development ACO has grown rapidly during the past decade. ACO is a stochastic approach that has been successfully applied to solve different challenging optimization problems, such as traveling salesman problems, quadratic assignment problems, resource-constrained project scheduling problems, permutation flowshop scheduling problems, and vehicle routing problems (Abdallah, Emara, Dorrah, & Bahgat, 2009; Blum & Roli, 2003; Bullnheimer, Hartl, & Strauss, 1999; Costa & Hertz, 1997; Deng & Lin, 2011; Dorigo, Birattari, & Stutzle, 2006; Dorigo & Blum, 2005; Dorigo, Di Caro, & Gambardella, 1999; Dorigo & Gambardella, 1997; Dorigo, Maniezzo, & Colorni, 1996; Gambardella, Taillard, & Dorigo, 1999; Gutjahr, 2000; Maniezzo & Colorni, 1999; Merkle, Middendorf, & Schmeck, 2002; Rajendran & Ziegler, 2004; Stutzle & Hoos, 2000). Accordingly, the ACO literature has also grown rapidly, and thus this study investigates the characteristics of the ACO literature during Jan. 1996 to Dec. 2010 using bibliometric and citation analysis. The specific analysis technique applied here applies bibliography counting to analyze and quantify the growth of the literature on a subject using various laws (Mishra, Panda, & Goswami, 2010; Shiau, 2011; Takeda & Kajikawa, 2009; Tsay, Jou, & Ma, 2000).

Tracing the productometric analysis of ACO publications requires performing citation analysis, which is necessary to judge the quality and impact of ACO papers and their global recognition. Citation reveals the links between pairs of documents, the one, which cites and the other, which is cited. Citation expresses the importance of the material cited, as authors frequently refer to previous material to support, illustrate, or collaborate on specific points. Citation analysis is an important tool in quantitative studies of science and technology. The quality of specific publications can be assessed based on the number of citations in the literature. The use of citation analysis in research on science history is based on a literary model of the scientific process.

The ISI database currently contains records for over 23 million value adding patent records in Chem/Biochem, Engineering, Electronics, going back to 1966 and covering over 22,000 journals. Generally, each record in the ISI database contains an English-language title, descriptive abstract, document type, and full information on cited references and number of citations. The bibliographic information includes the journal or other publication title, author name and affiliation, language of the original document, etc. Indexed document types include books and monographs, conferences, symposia, meetings, journal articles, reports, theses and dissertations.

This study used the search command to retrieve the phrases "Ant system", "Ant algorithm", "Ant colony system", "Ant colony optimization", "Ant colony algorithm", "Ant-based algorithm" or "Ant colony algorithms" from the descriptor field of the ISI database. The main study objective is to clarify the presence of ACO in published citations during 1996–2010 indexed in SCIE, SSCI

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and AH&CI retrieved using the Web of Science. This study has the following specific objectives:

(1) Explore the growth of the ACO literature.
(2) Identify citation growth of the ACO literature.
(3) Determine the time lag between paper publication and first citation.
(4) Clarify the domain wise distribution of citations.
(5) Determine a core of primary journals in which the literature on ACO in most heavily represented.
(6) Examine the distribution of citations among journals.
(7) Identify highly cited papers and track their citation life cycle.
(8) Reveal the distribution of the citing journals according to their impact factors.
(9) Identify the major contributing countries that publish the largest numbers of ACO articles and clarify the distribution of citing papers based on country of publication.
(10) Find the productivity distribution of authors and their institutions on this subject.
(11) Determine Cited Authorship Productivity and Lotka's Law.
(12) Plot the Bradford-Zipf graph.

2. Growth in the published ACO literature

The first paper published on ACO to appear in the ISI database dates to 1996. This study finds that the database contains 1372 journal articles dealing with ACO during 1996–2010. Table 1 lists the number of studies published each year. The table clearly indicates that before 2002, database contained just 36 items dealing with ACO literature. This shows that the collection of ACO papers may not be comprehensive during the initial stage in ISI database. The ISI database indicates that 2003 was the most significant year for the publication of literature. The ISI database contains 57 items dealing with ACO during that year. The article number peaked in 2009, when 250 articles were published. The literature published steadily increased from 2002 to 2010. Fig. 1 plots the annual numbers of published studies on ACO and clearly reveals that the sharpest increase occurred in 2009. Based on the figure, this study predicts that ACO will continue to rapidly grow. Fig. 1 also shows the cumulative growth of the ACO literature based on the ISI. Once again, the ISI database reveals growth in published works on ACO from 1999. Following 2003, the literature grows approximately linearly, exhibiting growth of about 50 items annually.

During 1996–2010, the ACO papers received 12,960 citations. The annual average number of citations was 864, and the average citations per article were 9.43. The number of citations peaked in 2010 at 2929 and continuous growth of citations was found throughout 1996–2010. The numbers of papers published and the citation rate peaked during 2009 as an inflow of earlier papers continued to receive citations. Table 1 shows the growth in the number of citations of the ACO literature over the 15 year period. Fig. 1 presents the growth and trends of citations of ACO publications per year, and clarifies the information in Table 1.

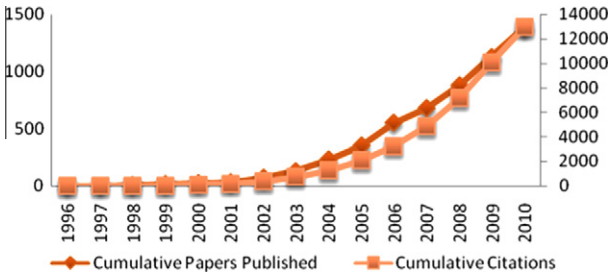

Fig. 1. Cumulative growth of ACO literature & citation trends during 1996–2010.

3. Citation frequency of ACO publications during 1996–2010

The development of any scientific and research subject depends heavily on its research output and intellectual publications. However, such outputs become redundant and profitless if scientists do not refer to them. If the citation likelihood is the same for every article, then the citation frequency should increase with the number of articles a journal publishes (Mishra et al., 2010). The data mostly supports this, although numerous articles are never cited. Considering its importance in significance, citation frequency of ACO publications was identified and listed in Table 2.

Eight-hundred and sixty-two of the 1372 papers were cited, while the remaining 500 and 10 papers were not. Of 1372 papers, one paper published in 1996 received 1902 citations in Computer Science and Artificial Intelligence, followed by 702 citations in 1999 in Computer Science, Theory and Methods, and 460 citations during 2000 in the same place. This data clearly reflects that the research on Computer Science conducted by ACO received global recognition.

4. Bradford Law and the journal literature

As discussed previously, the journal article is the single most widespread form of publication. In total, there are 517 journals published 1355 articles dealing with ACO. Of these, 299 journals published only one article on ACO. To identify a core group of journals containing a high proportion of articles on ACO, the Bradford

Table 1
Annual production of ACO literature and citation frequency of ACO publications.

Publication year	Papers published	% of 1372	Cumulative	Citation received	Cumulative citations
1996	1	0.07	1	0	0
1997	3	0.22	4	3	3
1998	3	0.22	7	14	17
1999	9	0.66	16	24	41
2000	12	0.88	28	72	113
2001	8	0.59	36	85	198
2002	39	2.86	75	206	404
2003	57	4.18	132	331	735
2004	100	7.33	232	549	1284
2005	120	8.80	352	790	2074
2006	198	14.52	550	1171	3245
2007	128	9.38	678	1594	4839
2008	198	14.52	876	2335	7174
2009	250	18.33	1126	2857	10031
2010	246	16.79	1372	2929	12960

Table 2
Citation frequency of ACO publications.

No. of times cited	No. of papers	No. of citation	Cumulative	No. of times cited	No. of papers	No. of citation	Cumulative
0	510	0	0	42	2	84	5544
1	196	196	196	43	1	43	5587
2	131	262	458	44	1	44	5631
3	92	276	734	45	2	90	5721
4	58	232	966	47	3	141	5862
5	44	220	1186	48	1	48	5910
6	43	258	1444	50	1	50	5960
7	35	245	1689	51	2	102	6062
8	24	192	1881	57	1	57	6119
9	16	144	2025	59	2	118	6237
10	19	190	2215	60	1	60	6297
11	12	132	2347	64	1	64	6361
12	16	192	2539	65	2	130	6491
13	16	208	2747	66	1	66	6557
14	9	126	2873	67	1	67	6624
15	8	120	2993	69	1	69	6693
16	6	96	3089	70	1	70	6763
17	9	153	3242	71	2	142	6905
18	14	252	3494	74	1	74	6979
19	11	209	3703	76	1	76	7055
20	5	100	3803	77	1	77	7132
21	4	84	3887	81	1	81	7213
22	2	44	3931	83	2	166	7379
23	7	161	4092	96	1	96	7475
24	5	120	4212	108	1	108	7583
25	4	100	4312	110	1	110	7693
26	4	104	4416	117	1	117	7810
27	3	81	4497	125	1	125	7935
28	6	168	4665	150	1	150	8085
29	4	116	4781	160	1	160	8245
30	3	90	4871	190	1	190	8435
31	2	62	4933	192	1	192	8627
32	4	128	5061	195	1	195	8822
33	1	33	5094	200	1	200	9022
34	3	102	5196	217	1	217	9239
35	1	35	5231	268	1	268	9507
36	2	72	5303	389	1	389	9896
37	1	37	5340	460	1	460	10356
38	1	38	5378	702	1	702	11058
41	2	82	5460	1902	1	1902	12960

law has been widely employed to study the distribution of literature among journals. Fig. 2 illustrates the Bradford plot – the cumulative number of papers published by each journal against the logarithm of ranks of its article amount – for the journal literature on ACO. If the plot for data on a specific subject revealed a discontinuity of S-slope in the Bradford method, the phenomenon might result from the dispersion of the literature on the subject. Clearly, Fig. 2 cannot produce a curve like the S-shape as the typical Bradford plot. The curve on ACO fails to reproduce the final droop in the Bradford plot, the result suggests that the literature on ACO is not spread across numerous different journals. The approximately linear portion appears after the journal rank of about 23. The top 23 journals can be considered the core journals in the ACO literature.

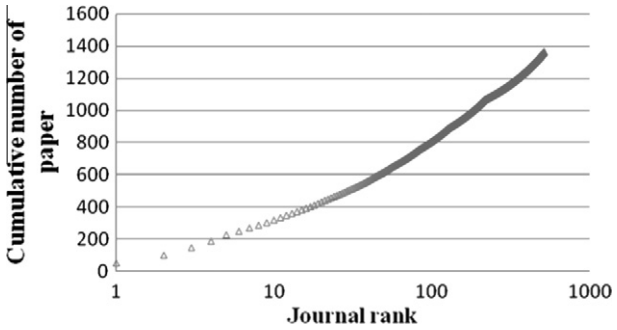

Fig. 2. The Bradford plot of the ACO literature.

Table 3 ranks different journals and number of articles published by them. To avoid making the ranking table too long, the cut off value was set at six articles. Thus, Table 3 lists 38 journals which include at least published six articles on ACO in terms of number of article count and impact factor. Bradford Law claims that a sample of articles can be divided into three equal sets, where each set will contain the amount of journal on a given topic in proportions of $1:n:n^2$, and this may also be true for the literature on ACO. The present sample could be divided into three parts, each containing approximately 450 records. The numbers of journals in each of the three parts were 23:98:396, representing approximate proportions of 1:4:16, so $n = 4$. The first 23 journals thus comprise approximately 33% of literature, while the remaining 67% is scattered among 494 journals. This statistic shows that the literature on ACO is relatively scattered. This statistic also illustrates that 299 journals published only one article dealing with ACO, and the first three journals together cover approximately 10.64% of the literature. The journal with the largest number of articles was Expert systems with applications, with 50 articles, representing 3.63% of the total. This was followed by ant colony optimization and swarm intelligence with 49 articles (3.58%), and International journal of advanced manufacturing technology with 47 citations (3.44%).

5. Journal-wise citation of papers on ACO

From the citation perspective, the law describes a quantitative relationship between journals. Fig. 3 shows the Bradford plot –

Table 3
Journals publishing more than six articles during 1996–2010.

	Source title	Record count	% of 1364	Impact factor
1	Expert systems with applications	50	3.66	2.9
2	Ant colony optimization and swarm intelligence, proceedings	49	3.58	0.5
3	International journal of advanced manufacturing technology	47	3.44	1.1
4	Computers & operations research	40	3.44	2.1
5	European journal of operational research	40	2.93	2.1
6	International journal of production research	22	1.61	0.8
7	Applied soft computing	21	1.54	2.4
8	Engineering optimization	17	1.24	1.0
9	Applied mathematics and computation	16	1.17	1.1
10	IEEE transactions on evolutionary computation	16	1.17	4.6
11	Computers & industrial engineering	15	1.10	1.5
12	Journal of the operational research society	15	1.10	1.0
13	Applications of evolutionary computing, proceedings	12	0.88	0.5
14	Engineering applications of artificial intelligence	11	0.80	1.4
15	Journal of systems engineering and electronics	11	0.80	0.3
16	Annals of operations research	10	0.73	1.0
17	Computers & structures	10	0.73	1.4
18	IEEE transactions on power systems	10	0.73	1.9
19	International journal of innovative computing information and control	10	0.73	2.9
20	Pattern recognition letters	10	0.73	1.3
21	International journal of production economics	9	0.66	2.1
22	IEEE transactions on systems man and cybernetics part b-cybernetics	8	0.59	3.0
23	Information sciences	8	0.59	3.3
24	Structural and multidisciplinary optimization	8	0.59	1.5
25	Chinese journal of electronics	7	0.51	0.2
26	Dynamics of continuous discrete and impulsive systems-series b-applications & algorithms	7	0.51	0.1
27	IEEE transactions on antennas and propagation	7	0.51	2.0
28	International journal of computers communications & control	7	0.51	0.4
29	Sensors	7	0.51	1.8
30	Simulated evolution and learning, proceedings	7	0.51	0.5
31	Advances in natural computation, pt 2	6	0.44	0.5
32	Applications of evolutionary computing	6	0.44	0.5
33	Artificial life	6	0.44	2.0
34	Electric power systems research	6	0.44	1.3
35	Evolutionary computation in combinatorial optimization, proceedings	6	0.44	0.5
36	IEEE transactions on systems man and cybernetics part a-systems and humans	6	0.44	2.0
37	IEEE transactions on systems man and cybernetics part c-applications and reviews	6	0.44	2.0
38	International journal of electrical power & energy systems	6	0.44	1.6

the cumulative number of papers for each journal against the logarithm of its rank – for journals citing ACO publications. The figure clearly illustrates the S-shape as the typical Bradford-Zipf plot, although the initial rise is somewhat faster than average. The approximately linear portion appears at the journal rank of 40. The top 40 may be considered the core journals of ACO.

During 1996–2010, a total of 517 journals contained 12,960 citations involving works dealing with ACO. The journal with the largest number of citations was IEEE transactions on systems man and cybernetics part b-cybernetics, with 2033 citations, representing 15.68% of the total. This was followed by Artificial life with 783 citations (6.04%), and IEEE transactions on evolutionary computation with 674 citations (5.20%). Table 4 lists the top 38 journals in terms of number of citations and impact factor.

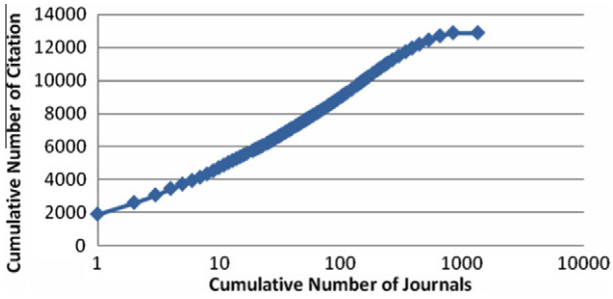

Fig. 3. The Bradford plot of the ACO literature.

6. Domain-wise distributions of citations

The basic objective of Table 5 is to identify the different subject areas of journals citing literature on ACO during 1996–2010. Literature on ACO is cited in journals dealing with 100 broad subject areas, ranging from Computer Science to Food Science & Technology. Table 5 lists these subjects, as well as the number of citations for each, arranged in descending order of frequency.

From the citation perspective, the findings indicate that the literature on Computer Science, Artificial Intelligence most frequently cited ACO, recording 4637 citations. This was followed by Computer Science, Theory & Methods with 3965 citations and Operations Research & Management Science with 2623 citations. Other subject areas also cited ACO frequently.

7. Highly cited papers dealing with ACO during 1996–2010

The potentiality and credibility of a researcher and their research findings are frequently judged by the frequency with which their works are cited. The assumption is that a work that is cited more frequently has higher research value and impact. Table 6 lists 41 frequently cited works dealing with ACO, together with their bibliographical details. Paper 1 received 1902 citations during 1997–2010, of which approximately thirty were self-citations. This paper began to receive citations only from one year after publication, with an average of 126.8 citations annually and 442 journals cited this paper. Paper 2 received 702 citations during 2000–2010, approximately twenty of which were self-citations. This paper

Table 4
Journals in terms of number of citations.

	Journal title	Paper cited	Average citations per year	Impact factor
1	IEEE transactions on systems man and cybernetics part b-cybernetics	2033	254.1	3.0
2	Artificial life	783	103.5	2.0
3	IEEE transactions on evolutionary computation	674	42.1	4.6
4	European journal of operational research	664	16.6	2.1
5	Journal of the operational research society	535	35.7	1.0
6	Computers & operations research	422	10.6	2.1
7	Annals of operations research	267	26.7	1.0
8	IEEE transactions on power systems	205	20.5	1.9
9	Ant colony optimization and swarm intelligence, proceedings	194	4.0	0.5
10	International journal of advanced manufacturing technology	158	3.4	1.1
11	IEEE transactions on systems man and cybernetics part a-systems and humans	129	21.5	2.0
12	Applied mathematics and computation	123	7.7	1.1
13	International journal of production research	120	5.5	0.8
14	Expert systems with applications	120	2.4	2.9
15	Computers & industrial engineering	100	6.7	1.5
16	Information sciences	95	11.9	3.3
17	Reliability engineering & system safety	81	13.5	1.9
18	Applications of evolutionary computing	79	13.2	0.5
19	IEEE transactions on antennas and propagation	67	9.6	2.0
20	Journal of heuristics	62	12.4	1.3
21	Electric power systems research	62	10.3	1.3
22	Applied soft computing	62	3.0	2.4
23	Applications of evolutionary computing, proceedings	59	4.9	0.5
24	Engineering optimization	59	3.5	1.0
25	Pattern recognition letters	50	5.0	1.3
26	Robotics and computer-integrated manufacturing	44	7.3	1.7
27	International journal of production economics	41	4.6	2.1
28	Engineering applications of artificial intelligence	33	3.0	1.4
29	Mathematical and computer modeling	32	6.4	1.1
30	Computers & structures	31	3.1	1.4
31	International journal of intelligent systems	27	5.4	1.2
32	Computers & mathematics with applications	25	5.0	1.2
33	Structural and multidisciplinary optimization	25	3.1	1.5
34	Evolutionary computation in combinatorial optimization, proceedings	21	3.5	0.5
35	Water resources management	19	3.8	2.0
36	Advances in engineering software	15	3.0	1.0
37	IEEE transactions on systems man and cybernetics part c-applications and reviews	15	2.5	2.0
38	International journal of computers communications & control	15	2.1	0.4

received citations during the first year after publication and continued to receive citations through the study period. The annual average citation frequency was 63.8 and 247 journals cited this paper. Paper 3 received 460 citations during 2002–2010, approximately 10 of which were self-citations. This paper received citations from two year after its publication and continued to receive citations through the study period. The paper was cited in 112 journals and the average annual citation frequency was 41.8. However, the citation frequency exhibited a declining trend during the last year. Paper 4 received 268 citations during 2004–2010, approximately ten of which were self-citations. This paper began to receive citations only from one year after its publication and continued to be cited throughout the study period. 141 journals cited this paper. The average annual citation frequency was 33.5.

8. Lotka's Law and author productivity

Table 7 lists 2488 authors, including single authors and co-authors, who contributed to the publication of 1372 articles dealing with ACO. On average, each author published 0.55 papers. The vast majority (1562 authors, or 71%) contributed only one article and did so with the assistance of co-authors. The statistics thus differ from Lotka's Law, which states that roughly 60% of authors contribute just one paper (Tsay et al., 2000). Furthermore, a little over 1% of the authors contributed more than ten articles. One author contributed as many as 25 articles, while the second and third ranking authors in terms of numbers of articles contributed accounted for 19 articles. This shows that the ACO literature contains an extremely large number of publications contributed by a single author. Table 8 lists the 40 most productive authors, each of whom published more than seven articles, together with the number of articles published. Notably, the data on the top three authors indicates that their publications dealing with ACO appeared between 1996 and 2010 in Belgium, 2007 and 2010 in Iran, and 1998 and 2007 in Germany, respectively. This study finds that Dorigo, who first proposed ACO, was the most prolific author writing on ACO, and all of his works focus on this field.

9. Core authors cited in ACO papers

This study also aims to identify the key authors on ACO from the citation perspective. It is universally accepted in the bibliometric world that the influence of the publications of an author increases with the number of times their works are cited. An author is considered influential if researchers in a similar filed frequently cite their contributions (Mishra et al., 2010).

One author obtained as many as 4155 citations, while the second and third ranking authors in terms of numbers of citations accounted for 2217 and 1492 citations, respectively. This shows that the ACO literature contains an extremely large number of citations contributed by a small number of authors. Table 9 lists the 40 most productive authors by citation perspective, each of whom obtained more than sixty-four citations, together with the number of articles published. The data on the top three authors indicates that their citation appeared between 1997 and 2010, 1997 and 2010, and 1998 and 2010, respectively. Notably, most of the cores cited authors are also the highly productive authors. This study also finds that Dorigo, who was the most prolific author writing on ACO, obtained the most citations on this field.

Table 5
Citations of the literature on ACO in different subject areas during 1996–2010.

Subject	Citation
Computer Science, Artificial Intelligence (266)	4637
Computer Science, Theory & Methods (269)	3965
Operations Research & Management Science (271)	2623
Automation & Control Systems (120)	2398
Computer Science, Cybernetics (27)	2183
Computer Science, Interdisciplinary Applications (185)	1230
Management (59)	1208
Engineering, Electrical & Electronic (226)	1126
Engineering, Industrial (113)	831
Computer Science, Information Systems (75)	531
Engineering, Manufacturing (111)	483
Mathematics, Applied (67)	332
Engineering, Multidisciplinary (79)	316
Engineering, Civil (66)	280
Water Resources (21)	185
Computer Science, Software Engineering (43)	184
Engineering, Chemical (17)	153
Telecommunications (55)	145
Computer Science, Hardware & Architecture (33)	129
Statistics & Probability (13)	127
Construction & Building Technology (19)	96
Chemistry, Analytical (18)	94
Energy & Fuels (14)	87
Instruments & Instrumentation (19)	78
Robotics (14)	75
Engineering, Mechanical (17)	69
Mathematics, Interdisciplinary Applications (26)	66
Chemistry, Multidisciplinary (19)	61
Environmental Sciences (13)	46
Transportation Science & Technology (16)	45
Physics, Applied (13)	42
Mechanics (26)	41
Optics (12)	26
Materials Science, Multidisciplinary (11)	14

Lotka's Law was used to measure author productivity. Specifically, this study tested whether the author data conformed to the original formulation of Lotka. Lotka's Law can be expressed as $y = c/X^n$, where y = percentage of the number of authors published x articles relative to total number of authors, x = number of articles published by an author, c = a constant with value 0.6079, and Lotka's Law defines n as the slope of the log–log plot (Tsay et al., 2000).

Lotka's Law describes the frequency of publication by an author in a given field and states that the number of authors making multiple articles to the literature on a given field is about $1/n^2$ of those making one article. This means that approximately 60% of authors writing on a given field have just one publication; 15% have two publications ($1/2^2$ of 60); 7% have three publications ($1/2^3$ of 60) and so on. Furthermore, according to Lotka's Law of scientific productivity, only 6% of authors dealing with a given field produce more than ten articles.

Fig. 4 shows the data on ACO author productivity via a fitted line. The red[1] solid-line indicates the fitted line and is based on all data. The data on authors with high numbers of publications are quite scattered and may not be representative. If data on authors with more than 11 publications are omitted, the least square fit follows this fitted line. Notably, the literature suggests that data on high productivity authors should be omitted to achieve good fit.

10. International distribution of citing journals

Seventy-three countries were represented in the group publishing ACO literature. Table 10 lists the international distribution of ACO literature by country. Although ISI is a British database, China is the leading country in terms of publishing literature dealing with ACO. About 21.63% of the ACO literature was published in China. The USA (10.26%) and Taiwan (9.60%) ranked second and third, and were followed by Iran, India and Germany, each of which also contributed over 5% of the total literature. Turkey, Spain, Belgium, Italy, France, and Canada also contributed significantly to the literature on ACO. The involvement of scientists from so many countries in ACO research clearly suggests that ACO has attracted international attention.

To determine the number of citations each nation or country receives, Table 11 lists and statistically analyzes the data on the number of citations each country receives. The countries appearing in the "country of affiliation" field in the citing papers were recorded, yielding a total of 73 countries associated with 12960 citations. The countries most frequently citing ACO literature were: Belgium (3254 citations, or 20.10% of the total) with 33 institutions citing ACO research findings; followed by the Italy (2632, 15.30%) with 39 institutions citing ACO papers, and the Switzerland (1827, 10.44%) with 32 institutions citing ACO papers. The analysis thus reveals numerous countries citing ACO research findings in their respective research. Thus ACO research is based on international standards and has attracted global recognition. Notably, the top three highly productive countries are different from the countries receive most.

Examining the affiliations of authors contributing to the ACO literature is also essential. The authors in the present sample were affiliated with 982 institutes. Table 12 lists the top 31 most productive institutes, each of which published over 10 articles. Iran University of Science & Technology in Iran was the most productive institute in terms of its contribution to the ACO literature, contributing 43 articles. Meanwhile, University of Vienna in Austria, and Free University of Brussels in Belgium, ranked second and third, respectively. The top 27 productive institutes in terms of their contribution to ACO literature together published 436 articles, accounting for 32% of the ACO literature. Most of the highly productive institutes were major universities. This shows that ACO research is concentrated in major universities rather than being dispersed among private companies.

11. Conclusion

Citation and impact factor clearly indicate the quality of the literature on ACO. This investigation shows that, during the last 15 years, ACO publications received 12960 citations spread among 517 journals, with impact factor ranges varying from 0.01 to 5.00. Research on ACO was cited by 982 world reputable institutions from 73 countries. This study examined the growth of the ACO literature, based on the ISI database, and tested the various characteristics of the literature using bibliometric techniques. The following results were obtained:

1. Following 2003, the literature grew approximately linearly, a rate of approximately 50 records per year, and peaked in 2009 with about 250 records.
2. The journal literature on ACO roughly conforms to the typical S-shape Bradford-Zifp plot during the initial stage, but does not show the final droop during the later stage. Clearly ACO is not yet widely referred to in the journal literature.
3. The Bradford-Zipf plot reveals 23 core journals. Approximately 33% of the literature is concentrated in the first 23 journals, with the remaining 67% being scattered among the other 494 journals.
4. The journal with the largest number of articles was Expert systems with applications, with 50 articles, representing 3.63% of the total, and the journal with the largest number of citations

[1] For interpretation of color in Fig. 4, the reader is referred to the web version of this article.

Table 6
Highly cited papers on ACO.

Paper	Authors_Title Source_Title Publication_Year	Total citations	Average citations per year
1	Dorigo, M; Maniezzo, V; Colorni, A. Ant system: Optimization by a colony of cooperating agents. IEEE Transactions On Systems Man And Cybernetics Part B-Cybernetics. 1996	1902	126.8
2	Dorigo, M; Di Caro, G; Gambardella, LM. Ant algorithms for discrete optimization. Artificial life. 1999	702	63.8
3	Stutzle, T; Hoos, HH.MAX-MIN Ant System. Future Generation Computer Systems. 2000	460	41.8
4	Blum, C; Roli, A. Metaheuristics in combinatorial optimization: Overview and conceptual comparison. ACM Computing Surveys. 2003	268	33.5
5	Dorigo, M; Blum, C. Ant colony optimization theory: A survey. Theoretical Computer Science. 2005	195	32.5
6	Dorigo, M; Gambardella, LM. Ant colonies for the traveling salesman problem.Biosystems. 1997	389	27.8
7	Dorigo, M; Birattari, M; Stutzle, T. Ant colony optimization – Artificial ants as a computational intelligence technique. IEEE Computational Intelligence Magazine. 2006	83	20.8
8	Dorigo, M; Bonabeau, E; Theraulaz, G. Ant algorithms and stigmergy. Future Generation Computer Systems-The International Journal of Grid Computing Theory Methods And Applications. 2000	200	18.2
9	Gambardella, LM; Taillard, ED; Dorigo, M. Ant colonies for the quadratic assignment problem. Journal of The Operational Research Society. 1999	217	18.1
10	Parpinelli, RS; Lopes, HS; Freitas, AA. Data mining with an ant colony optimization algorithm. IEEE Transactions On Evolutionary Computation. 2002	160	17.8
11	Blum, C. Ant colony optimization: Introduction and recent trends. Physics Of Life Reviews. 2005	65	16.3
12	Maniezzo, V; Colorni, A. The ant system applied to the quadratic assignment problem. IEEE Transactions On Knowledge And Data Engineering. 1999	192	16.0
13	Rajendran, C; Ziegler, H. Ant-colony algorithms for permutation flowshop scheduling to minimize makespan/total flowtime of jobs. European Journal of Operational Research. 2004	108	15.4
14	Blum, C; Dorigo, M. The hyper-cube framework for ant colony optimization. IEEE Transactions On Systems Man And Cybernetics Part B-Cybernetics. 2004	96	13.7
15	Costa, D; Hertz, A. Ants can color graphs. Journal of The Operational Research Society. 1997	190	13.6
16	Tasgetiren, MF; Liang, YC; Sevkli, M; et al. A particle swarm optimization algorithm for makespan and total flowtime minimization in the permutation flowshop sequencing problem. European Journal of Operational Research. 2007	67	13.4
17	Merkle, D; Middendorf, M; Schmeck, H. Ant colony optimization for resource-constrained project scheduling. IEEE Transactions On Evolutionary Computation. 2002	117	13.0
18	Bullnheimer, B; Hartl, RF; Strauss, C. An improved ant system algorithm for the vehicle routing problem. Annals Of Operations Research. 1999	150	12.5
19	Socha, K; Dorigo, M. A colony optimization for continuous domains. European Journal Of Operational Research. 2008	50	12.5
20	Moore, JH; Williams, SM. Epistasis and Its Implications for Personal Genetics. American Journal Of Human Genetics. 2009	24	12
21	Blum, C. Beam-ACO – hybridizing ant colony optimization with beam search: an application to open shop scheduling. Computers & Operations Research. 2005	71	11.8
22	Merz, P; Freisleben, B. Fitness landscape analysis and memetic algorithms for the quadratic assignment problem. IEEE Transactions On Evolutionary Computation. 2000	125	11.4
23	Reimann, M; Doerner, K; Hartl, RF. D-Ants: Savings Based Ants divide and conquer the vehicle routing problem. Computers & Operations Research. 2004	77	11.0
24	Sim, KM; Sun, WH. Ant colony optimization for routing and load-balancing: Survey and new directions. IEEE Transactions On Systems Man And Cybernetics Part A-Systems And Humans. 2003	83	10.4
25	Gutjahr, WJ. Graph-based Ant System and its convergence. Future Generation Computer Systems. 2000	110	10.0
26	Maier, HR; Simpson, AR; Zecchin, AC; et al. Ant colony optimization distribution for design of water systems. Journal Of Water Resources Planning And Management-Asce. 2003	76	9.5
27	Shelokar, PS; Jayaraman, VK; Kulkarni, BD. An ant colony approach for clustering. Analytica Chimica Acta. 2004	65	9.3
28	Bell, JE; McMullen, PR. Ant colony optimization techniques for the vehicle routing problem. Advanced Engineering Informatics. 2004	64	9.1
29	Stutzle, T; Dorigo, M. A short convergence proof for a class of ant colony optimization algorithms. IEEE Transactions On Evolutionary Computation. 2002	81	9.0
30	Ying, KC; Liao, CJ. An ant colony system for permutation flow-shop sequencing. Computers & Operations Research. 2004	57	8.1
31	Gutjahr, WJ. ACO algorithms with guaranteed convergence to the optimal solution. Information Processing Letters. 2002	70	7.8
32	Doerner, K; Gutjahr, WJ; Hartl, RF; et al. Pareto ant colony optimization: A metaheuristic approach to multiobjective portfolio selection. Annals of Operations Research. 2004	51	7.3
33	Gambardella, LM; Dorigo, M. An ant colony system hybridized with a new local search for the sequential ordering problem. Informs Journal On Computing. 2000	74	6.7
34	T'kindt, V; Monmarche, N; Tercinet, F; et al. An Ant Colony Optimization algorithm to solve a 2-machine bicriteria flowshop scheduling problem. European Journal of Operational Research. 2002	60	6.7
35	McMullen, PR. An ant colony optimization approach to addressing a JIT sequencing problem with multiple objectives. Artificial Intelligence in Engineering. 2001	66	6.6
36	Solnon, C. Ants can solve constraint satisfaction problems. IEEE Transactions on Evolutionary Computation. 2002	59	6.6
37	Maniezzo, V. Exact and approximate nondeterministic tree-search procedures for the quadratic assignment problem. Informs Journal on Computing. 1999	71	6.5
38	Hernandez, P; Gras, R; Frey, J; et al. Popitam: Towards new heuristic strategies to improve protein identification from tandem mass spectrometry data. Proteomics. 2003	51	6.4
39	Abbaspour, KC; Schulin, R; van Genuchten, MT. Estimating unsaturated soil hydraulic parameters using ant colony optimization. Advances in Water Resources. 2001	59	5.9
40	Yu, DW; Pierce, NE. A castration parasite of an ant-plant mutualism. Proceedings of The Royal Society of London Series B-Biological Sciences. 1998	69	5.3
41	Maniezzo, V; Carbonaro, A. An ANTS heuristic for the frequency assignment problem. Future Generation Computer Systems. 2000	48	4.4

Table 7
Author productivity.

No. of articles	No. of authors	% of 2488	Cumulative
1	1710	68.73	1710
2	492	19.77	2202
3	136	5.47	2338
4	60	2.41	2398
5	37	1.49	2435
6	13	0.52	2448
7	12	0.48	2460
8	8	0.32	2468
9	4	0.16	2472
10	4	0.16	2476
12	1	0.04	2477
13	3	0.12	2480
14	2	0.08	2482
16	2	0.08	2484
17	1	0.04	2485
19	2	0.08	2487
25	1	0.04	2488
Total	2488	100.00	

Table 8
Authors publishing more than seven articles.

	Author	Record count	% of 1372
1	Dorigo, M	25	1.83
2	Kaveh, A	19	1.39
3	Middendorf, M	19	1.39
4	Blum, C	17	1.25
5	Gutjahr, WJ	16	1.17
6	Hartl, RF	16	1.17
7	Afshar, Mh	14	1.03
8	Stutzle, T	14	1.03
9	Gambardella, Lm	13	0.95
10	Niknam, T	13	0.95
11	Zhang, J	13	0.95
12	Doerner, Kf	12	0.88
13	Birattari, M	10	0.73
14	Chen, L	10	0.73
15	Jayaraman, Vk	10	0.73
16	Merkle, D	10	0.73
17	Gagne, C	9	0.66
18	Gravel, M	9	0.66
19	Kulkarni, Bd	9	0.66
20	Solnon, C	9	0.66
21	Juang, Cf	8	0.59
22	Maier, Hr	8	0.59
23	Price, Wl	8	0.59
24	Runkler, Ta	8	0.59
25	Siarry, P	8	0.59
26	Tian, P	8	0.59
27	Toksari, Md	8	0.59
28	Xu, Bl	8	0.59
29	Bautista, J	7	0.51
30	Baykasoglu, A	7	0.51
31	Korosec, P	7	0.51
32	Marinakis, Y	7	0.51
33	Rajendran, C	7	0.51
34	Reimann, M	7	0.51
35	Silc, J	7	0.51
36	Sousa, Jmc	7	0.51
37	Talatahari, S	7	0.51
38	Tiwari, Mk	7	0.51
39	Wang, Zq	7	0.51
40	Ying, Kc	7	0.51

was IEEE transactions on systems man and cybernetics part b-cybernetics, with 2033 citations, representing 15.68% of the total.

5. The China is the leading publishing country (approximately 21.63% of the total) and Belgium is the leading country which receives citations (approximately 20.10% of the total).

Table 9
Authors obtained more than 64 citations.

Rank	Author	Number of citations	Average citation per article
1	Dorigo, M	4155	166.20
2	Maniezzo, V	2217	369.50
3	Gambardella, Lm	1492	114.77
4	Stutzle, T	775	55.36
5	Blum, C	768	45.18
6	Middendorf, M	393	20.68
7	Hartl, Rf	362	22.63
8	Gutjahr, Wj	350	21.88
9	Merkle, D	246	24.60
10	Strauss, C	238	47.60
11	Kulkarni, Bd	228	25.33
12	Jayaraman, Vk	228	22.80
13	Rajendran, C	176	25.14
14	Schmeck, H	175	35.00
15	Doerner, K	156	31.20
16	Mcmullen, Pr	150	37.50
17	Maier, Hr	149	18.63
18	Birattari, M	149	14.90
19	Simpson, Ar	147	24.50
20	Zecchin, Ac	145	29.00
21	Liang, Yc	140	23.33
22	Liao, Cj	134	26.80
23	Socha, K	130	26.00
24	Reimann, M	125	17.86
25	Shelokar, Ps	120	20.00
26	Gagne, C	120	13.33
27	Gravel, M	120	13.33
28	Price, Wl	119	14.88
29	Solnon, C	118	13.11
30	Ying, Kc	92	13.14
31	Shankar, R	91	15.17
32	Stummer, C	85	17.00
33	Shen, Q	79	19.75
34	Siarry, P	75	9.38
35	Yin, Py	69	17.25
36	Doerner, Kf	69	5.75
37	Shyu, Sj	66	13.20
38	Toksari, Md	65	8.13
39	Manfrin, M	64	16.00
40	Solimanpur, M	64	16.00

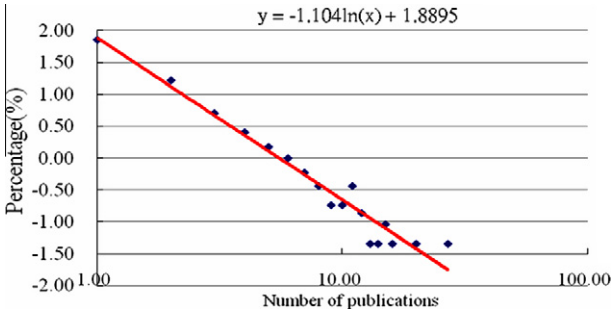

Fig. 4. Distribution of author productivity from the citation perspective.

6. The vast majority (71%) of authors contributed only one article citing ACO. Moreover, the author productivity distribution does not fit the original Lotka law.
7. Only slightly over 1% of authors contributed more than ten articles citing ACO. The author with the largest number of papers citing ACO contributed 27 such papers.
8. Analysis of author affiliated institutions illustrates that ACO research is concentrated in major universities.

The present study could be enhanced by including more bibliometric parameters and conducting a comparative study involving a similar field of research, such as particle swarm optimization.

Table 10
Country distribution.

	Country/territory	Record count	% of 1372
1	China	295	21.63
2	USA	140	10.26
3	Taiwan	131	9.60
4	Iran	123	9.02
5	India	81	5.94
6	Germany	75	5.50
7	Turkey	59	4.33
8	Spain	57	4.18
9	Belgium	55	4.03
10	France	49	3.59
11	Canada	46	3.37
12	England	44	3.23
13	Italy	41	3.01
14	Brazil	39	2.86
15	Austria	38	2.79
16	Japan	33	2.42
17	Australia	31	2.27
18	Switzerland	29	2.13
19	South Korea	20	1.47
20	Greece	19	1.39
21	Malaysia	18	1.32
22	Portugal	17	1.25
23	Singapore	15	1.10
24	Scotland	14	1.03
25	Thailand	13	0.95
26	Algeria	12	0.88
27	Poland	10	0.73

Table 11
Country distribution.

	Country/territory	Number of citation	Average citation per article
1	Belgium	3254	59.2
2	Italy	2632	64.2
3	Switzerland	1827	63.0
4	Germany	1037	13.8
5	USA	1031	7.4
6	Taiwan	897	6.8
7	Canada	747	16.2
8	China	716	2.4
9	Austria	669	17.6
10	India	668	8.2
11	France	613	12.5
12	Spain	514	9.0
13	Australia	334	10.8
14	Iran	331	2.7
15	Turkey	331	5.6
16	England	283	6.4
17	Brazil	256	6.6
18	Japan	157	4.8
19	Scotland	72	5.1
20	Singapore	70	4.7
21	Greece	69	3.6
22	Portugal	54	3.2
23	South Korea	29	1.5
24	Thailand	27	2.1
25	Algeria	27	2.3
26	Poland	14	1.4
27	Malaysia	10	0.6

Table 12
Most productive institutes in terms of the publication of ACO literature.

	Institution name	Record count	% of 1372
1	Iran Univ Sci & Technol	43	3.10
2	Univ Vienna	33	2.38
3	Free Univ Brussels	27	1.95
4	Indian Inst Technol	27	1.95
5	Sun Yat Sen Univ	23	1.66
6	Erciyes Univ	21	1.51
7	Zhejiang Univ	21	1.51
8	Univ Libre Bruxelles	18	1.30
9	Natl Chung Hsing Univ	16	1.15
10	Shanghai Jiao Tong Univ	16	1.15
11	Sharif Univ Technol	16	1.15
12	Univ Karlsruhe	16	1.15
13	Hong Kong Polytech Univ	14	1.01
14	Univ Politecn Cataluna	13	0.94
15	Huazhong Univ Sci & Technol	12	0.86
16	Amir Kabir Univ Technol	11	0.79
17	Dalian Univ Technol	11	0.79
18	Indian Inst Sci	11	0.79
19	Islamic Azad Univ	11	0.79
20	Nanjing Univ Aeronaut & Astronaut	11	0.79
21	Natl Taiwan Univ Sci & Technol	11	0.79
22	S China Univ Technol	11	0.79
23	Shiraz Univ Technol	11	0.79
24	Univ Granada	11	0.79
25	Univ Quebec	11	0.79
26	Chinese Acad Sci	10	0.72
27	City Univ Hong Kong	10	0.72
28	Nanjing Univ Sci & Technol	10	0.72
29	Univ Tecn Lisbon	10	0.72
30	Yangzhou Univ	10	0.72
31	Yuan Ze Univ	10	0.72

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